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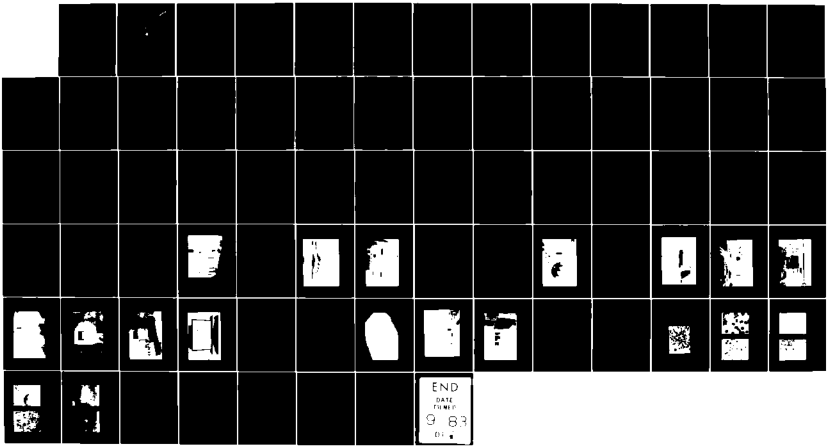

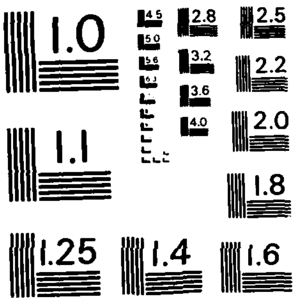
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NAVAL POSTGRADUATE SCHOOL

Monterey, California

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AN EXPERIMENTAL INVESTIGATION OF SOOT
BEHAVIOR IN A GAS TURBINE COMBUSTOR

by

Andrew Clarence Krug

June 1983

Thesis Advisor: D. W. Netzer

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The initial test series verified the adequacy of the test cell control apparatus as well as the extractive probe sampling system. The optical technique employed appeared to be adequate for the purpose of determining the mean particle diameter, but lacked sensitivity for use at the engine exhaust. Recommendations were made for facility and equipment improvements.

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An Experimental Investigation of Soot Behavior in a Gas Turbine Combustor

by

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ABSTRACT

A full scale gas turbine combustor test facility was designed, constructed, and initially operated to determine the performance of a gas turbine combustor and the associated combustion diagnostic apparatus.

The test cell was put through an initial series of four tests. The combustor was operated at 75% of normal operating conditions. A water cooled extractive probe sampling system was used to obtain a particulate sample and an optical system was used to measure the transmissivity inside the combustor and at the exhaust. The opacity of the exhaust gases was also monitored.

The initial test series verified the adequacy of the test cell control apparatus as well as the extractive probe sampling systems. The optical technique employed appeared to be adequate for the purpose of determining the mean particle diameter, but lacked sensitivity for use at the engine exhaust. Recommendations were made for facility and equipment improvements.

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I. INTRODUCTION

The United States Navy maintains one of the largest and most diverse high performance aircraft fleets in the world. To support this massive effort, the Navy utilizes a large number of jet engine test cells at its various jet engine rework facilities. Over the years, the use of such facilities has paid dividends in the form of lowering the number of engine failures in flight and in the cost reduction for necessary engine performance monitoring and modification. In short, the need for facilities in which high performance turbojet/turbofan engines can be safely overhauled and tested in a controlled environment has long since been proven. As such, the United States Navy has a vested interest in ensuring the uninterrupted operation of all its facilities.

Some of the inevitable by-products of the operation of a jet engine test cell are the increase in the noise in the immediate vicinity of the test cell and the expulsion of the combustion products into the atmosphere. Environmental protection is not only a natural concern of the local communities, but of the federal government, as well. In keeping with this concern, local governments have recently been adopting more stringent regulations to enhance the minimum pollution control guidelines issued by the Environmental Protection Agency. While military aircraft are exempt from such regulations, the engine test

facilities are not. This paradox results in a difficult dilemma. The problem to be solved by the Navy is how to test jet engines through the full range of their various operating conditions and, at the same time, meet all applicable pollution standards.

The Navy, in an effort to meet its responsibility to the local populace, has been investigating various methods of reducing and controlling the amounts of pollutants emitted as a result of jet engine testing. While technology may someday make pollution free, high performance aircraft engines a reality, the truth of the matter is that the basic jet engine design as well as the aircraft now in service will be with us for some time to come. The options available, then, become clearly defined. Either the Navy must modify existing test cells to control the released pollution, or modify the combustion process itself to produce a cleaner product. The first option is very expensive but is being accomplished on a limited basis at some facilities. Furthermore, the necessary physical modifications to the plant result in an uncertain ability to realistically test the engines. An alternate, cost effective, and operationally sound method seems to be the use of smoke suppressant fuel additives.

In recent years, many different smoke suppressant fuel additives have been developed. The Naval Air Propulsion Test Center has conducted evaluations on many of these additives in an effort to determine their relative effectiveness. The

results of their testing indicated that metallic based additives, such as Ferrocene, were most effective in reducing test cell exhaust plume opacity. The difficulty with some metallic based additives, however, is that their low melting temperatures can cause a build-up of deposits in the turbine of high performance engines. Therefore, there was sufficient need to find alternatives to such additives.

In answer to the need for both evaluating the effectiveness of the additives and understanding how they function to reduce opacity, a research program was initiated at the Naval Postgraduate School. A subscale test cell and a simulated gas turbine combustor were developed and refined until meaningful results could be achieved. Detailed description of the testing apparatus and data collecting techniques can be found in References 1 through 6.

The culmination of the research performed at the Naval Postgraduate School which was directed at smoke suppressant fuel additives and which used the original test apparatus was conducted by Bramer and Netzer [Ref. 6]. Six smoke suppressant fuel additives were tested in order to determine their effects on test cell stack exhaust gas opacity, volume to surface mean diameter of the particulate matter, exhaust particulate mass concentrations, and NOx concentrations. The additives ferrocene, DGT-2, and 12% Cerium Hex-Cem were found to be the most effective. The latter was significant in that cerium is a rare earth and has a substantially higher melting temperature than

iron. Additionally, it was found that the fuel additives that reduced stack opacity also reduced exhaust particulate mass concentration without reducing average particle diameter. Finally, NOx concentration at the test cell stack exhaust was not significantly changed by any of the fuel additives tested.

While the results obtained from this research were significant and provided much needed information on the capabilities and limitations of different smoke suppressant fuel additives, it was clear that additional research was necessary due to the need to clarify the mechanisms by which the additives worked and due to the constraints imposed by the testing apparatus. In particular, it was recommended that tests be conducted using an actual gas turbine combustor in place of the simulated ramjet-type dump burner. The cell for such testing stemmed from the fact that the atomization and air dilution processes were somewhat different in the two different configurations. The mass flow rate, operating pressure, fuel residence time, and inlet air temperature all have an effect on the combustion process.

In addition to the aforementioned reasons for the need for further research, it is widely admitted that much needs to be learned of the processes by which particulates are formed and consumed in gas turbine combustion. The physical mechanisms that allow smoke suppressant fuel additives to be successful are also not sufficiently understood. Even the locations in the combustion process at which particulate size and/or number

density are reduced can only be speculated. To understand the mechanisms is to understand why certain additives work better than others. To effectively study these mechanisms, it is necessary to simultaneously apply various diagnostic techniques within the combustor. This serves to both increase confidence in the validity of the data and to determine the most accurate and cost effective techniques.

The above discussion indicates the need for a well instrumented test facility with a fully operational combustion system from an in service gas turbine engine. The efforts documented in this thesis provided such an apparatus. Much of the instrumentation and data acquisition techniques that were used were based upon earlier work by other investigators. For example, the basic design of the water cooled sampling probe was obtained from the work of Samuelson and Hock of the University of California, Irvine [Ref. 10]. The light extinction measurement technique was used previously at the Naval Postgraduate School to make measurements of particle sizes and concentrations at the exhaust of the subscale test cell.

The combustor from the Allison T63-A5A engine was chosen in order to meet the requirement for the use of an actual gas turbine combustor. At the same time, it enabled the tests to be conducted within the mass flow limits of the air supply which currently existed at the Naval Postgraduate School laboratory facilities.

The test apparatus was constructed in such a manner as to provide a variety of information about the combustion process and its products. The purpose of the apparatus was to provide a data base from which the effectiveness and functioning mechanisms of smoke suppressant fuel additives could be determined. This entailed the measurement of the concentration and size of soot particles and gas temperatures at various locations inside the combustor and at the combustor exhaust. Two data gathering techniques were used to obtain the particulate data. Firstly, a three-frequency light extinction measurement technique was used at the exhaust and at a single location within the combustor. Secondly, particulates were collected in the combustor with an extractive probe. The collected particulates were analyzed using a scanning electron microscope (SEM). To supplement this information, a thermocouple probe was constructed which could be used to provide an axial temperature profile for each experiment.

II. EXPERIMENTAL APPARATUS

A. TEST CELL AND COMBUSTOR

The primary test article used in this experiment was a gas turbine combustor (T63) mounted externally on a static test stand (Figure 1). The T63-A-5A engine was built by Allison Detroit Diesel and was utilized in several operational aircraft, most notably, the Army OH-6A helicopter. The combustor incorporated in this engine possessed several unique characteristics which made it attractive for use in the present investigation. The combustor is illustrated in Figure 2.

There were specific design features of this combustor which made it singularly useful for this investigation. First, this full scale combustion system was of singular chamber, reverse flow design. The single chamber feature was convenient because the entire combustion system could be mounted and studied, a more preferable option than attempting to mount only a portion of the popular annular, or multiple chamber designs. The reverse flow feature greatly simplified the mounting of optical detection windows and supplied a buffer region of cooler, cleaner air between the windows and the primary combustion zone. Furthermore, the take-off rated airflow of this combustion system was 3.2 lb/sec, and this relatively small air flow rate fit nicely with the existing high pressure air supply system at the propulsion laboratory. A larger air flow rate would have severely limited

the run time for each experiment. Lastly, the combustor utilized a single igniter plug and fuel nozzle, greatly simplifying the maintenance and supply part problems.

High pressure air was supplied to the combustor by the large high pressure air reservoir maintained at the propulsion laboratory (Figure 3). The reservoir was pressurized to approximately 3000 psi by a Joy model compressor before each run (Figure 4). At this pressure, the reservoir could provide nearly fifteen minutes of run time. The air feed line was fitted with a dome pressure regulator and a sonically choked nozzle to provide precise metering of the flow rate through the test cell during engine operation. Varying the nitrogen pressure to the dome regulator proportionally varied the upstream pressure existing at the sonically choked nozzle. The mass flow rate through the sonic choke was directly proportional to that pressure ($\dot{m}=K\frac{P}{\sqrt{T}}$). The nitrogen pressure to the dome regulator was remotely controlled from a panel in the control room. In order to simulate typical operational inlet air conditions for the combustor, a vitiated air heater could be used in line with the high pressure air source. The heater allowed high inlet air temperatures to be attained. Utilizing a sudden expansion can type combustor, part of the supply air reacted with the fuel (ethylene - C_2H_4) to produce the high temperature combustion products. Dilution air was mixed with these gases to lower the temperature to the desired value. Figure 5 presents the theoretical combustion temperature as a function of fuel-air ratio. In addition,

oxygen was introduced into the heated air downstream of the heater to replace the oxygen used in the combustion process. Again, the flows of ethylene and oxygen were metered by means of sonic chokes and remotely controlled pressure regulators. Calibration of the oxygen and ethylene metering systems produced the following flow equations:

$$\dot{m}_{O_2} = P_t \; (.0000847) \qquad [\text{lbm/sec}] \qquad (1)$$

$$\dot{m}_{C_2H_4} = .000722 \, \frac{P_t}{\sqrt{T_t}} \qquad [\text{lbm/ses}] \qquad (2)$$

A complete schematic of the air supply system is provided in Figure 6.

The exhaust gases produced in the combustor exited through a fixed area turbine nozzle. Subsequently they entered a locally manufactured aft closure and variable area exhaust nozzle. The exhaust nozzle exit aperture (Figure 7) could be manually varied to supply the necessary back pressure for the combustor. Without such a device, the pressure drop across the combustor liner could have caused failure of the liner.

Operation of the test cell was designed to be a two person procedure when the gas sampling probe was used. One individual was positioned in the test cell control room to control the combustor operation and the other was stationed in the test cell (separated from the combustor by a steel blast shield) to operate the sampling probe.

Other subsystem components included a fuel supply system, an instrumentation package, various optical transmission measurement systems, and a water cooled sampling probe system. These items will be fully described below.

B. FUEL SYSTEM

The fuel system consisted of a twenty-gallon, high pressure, fuel tank, a remote control panel, two precision metering pumps for fuel additive injection, high pressure nitrogen bottles, and remotely controlled, electrically operated solenoid valves (Figure 8). The fuel tank (Figure 9) was equipped with an electrically activated vent valve. A single fuel line connected the tank to the combustor through an electrically operated shut-off valve. The fuel tank was pressurized with a gaseous nitrogen by a hand operated regulator located on the control panel (Figure 10). Fuel flow rate to the combustor was controlled by precise regulation of the fuel tank pressure. The fuel nozzle utilized by the T-63 combustor was calibrated for fuel flow rate versus the drop in pressure across the nozzle. By monitoring the combustor chamber pressure and regulating the upstream pressure on the fuel, the flow rate was accurately adjusted. A calibration equation for fuel flow rate versus differential pressure was:

$$\dot{m}_f = \Delta P_f \, (1.614 \times 10^{-4}) \qquad [\text{lbm/sec}] \qquad (3)$$

Two Eldex, Model E, precision metering pumps, shown in Figure 11, could be used for fuel additive injection into the

fuel line just upstream of the combustor. A swirl type mixer was incorporated to insure that mixing of the fuel and additive occurred prior to entry into the combustor. Each pump was capable of delivering between 0.2 and 5.0 ml/min of fuel additive. The flow rate versus pump micrometer setting was pre-calibrated and the results are shown in Figure 7 of Reference 5.

C. TRANSMISSOMETER

The transmissometer utilized during this study was a Leads and Northrop model 6597. The transmissometer consisted of a white light source, a detector unit, and a signal conditioner/display unit. The white light source and the detector unit were mounted across the exhaust stream to provide a read-out of exhaust stream opacity. Figure 12 shows the source and detector. Figure 13 shows the signal conditioner/display unit.

D. OPTICAL DETECTOR SYSTEM

Light transmission and detection techniques utilized during the studies conducted on the subscale turbojet test cell were adopted for use in this investigation. Non-intrusive data collection techniques were considered preferable to extractive probe data collection because the flow conditions within the combustor would remain undisturbed. In an effort to accomplish this non-intrusive data collection, the collimated white light sources and detectors used by Thornburg, Bramer, and Netzer [Refs. 5,6] were placed across the exhaust stream and just aft of the primary combustion zone in the combustor. The equipment

mentioned above has been thoroughly described in several previous reports [Refs. 1-6]. For report clarity, however, a brief recapitulation of the apparatus and methods for data reduction follow.

Two source/detection systems were used during this investigation. Because alignment of the source/detector pairs was critical, free standing adjustable tables were used to mount the apparatus permanently. Since the tables were independent of the test stand, no vibrational problems were encountered. The source/detector pairs and their position relative to the test stand can be seen in Figure 1.

The white light source was provided by a projector with a 750 watt incandescent bulb. A piece of diffuse glass placed between the lamp and the projector lens ensured a beam of light of uniform intensity. The beam was then focused on a .040 inch diameter pinhole. By routing the divergent light exiting the pinhole through a 31.5 mm diameter achromatic lens with an 80 mm focal length, a collimated beam of light was achieved. The collimated beam of light was then reduced to a .50 inch diameter by passing it through a reducer tube. The collimated white light source is shown in Figure 14.

The light detectors, shown in Figure 15, had a single entry point for the beam of collimated light. This entry point was a .25 inch I.D. tube fashioned to minimize forward scattered light effects [Ref. 8]. After entering the detector box, the collimated beam passed through two beam splitters, resulting

in three distinct beams of light. In order to pass only the desired light frequencies, the beams were then directed through narrow pass filters and onto the photodiodes. Neutral density filters were used as needed to avoid overdriving the photodiodes. The detector units incorporated narrow pass filters with wavelengths of 10,140, 6500, and 4500 angstroms. The paths followed by the light inside the detectors are shown schematically in Figure 16.

The light source/detector pairs were designed and built to measure the fraction of light transmitted through the combustion products (the transmissivity). This value is determined by comparing the photodiode output without particles present to that with particles present. The voltage output of each photodiode was continuously recorded on a strip chart recorder.

In this investigation, it was desired to determine the particle size and mass concentration both inside the combustor and at the combustor exhaust. K. L. Cashdollar [Ref. 8] successfully applied Mie scattering theory to the measurement of smoke particle size and concentration in a cloud of smoke. Bouguer's law [Ref. 8] for the transmission of light through a cloud of uniform particles can be written:

$$T = \exp(-QAnL) = \exp[-(3QCmL/2\rho d)] \tag{4}$$

where (T) is the fraction of light transmitted, (Q) is the dimensionless extinction coefficient, (A) is the cross sectional area of a particle, (n) is the number concentration of the

particles, (L) is the path length the light beam traverses, (Cm) is the mass concentration of particles, (ρ) is the density of an individual particle, and (d) is the particle diameter.

A more useful relationship was developed by Dobbins [Ref. 9]. Dobbins revised Bouguer's transmission law to allow for a distribution of particle sizes:

$$T = \exp\ [-(3\overline{Q}CmL/2\rho d_{32})] \tag{5}$$

where ($\overline{Q}$) is an average extinction coefficient and (d_{32}) is the volume-to-surface mean particle diameter. Taking the natural logarithm of equation (5) and writing it for a specific wavelength of light:

$$\ln\ [T_{\lambda}] = \overline{Q}_{\lambda}\ [-3CmL/2\rho d_{32}] \tag{6}$$

Assuming Cm, L, ρ, and d_{32} remain constant, the ratio of the natural logs of the transmittances for two wavelengths of light is:

$$\frac{\ln\ [T_{\lambda 1}]}{\ln\ [T_{\lambda 2}]} = \frac{\overline{Q}_{\lambda 1}}{\overline{Q}_{\lambda 2}} \tag{7}$$

A Mie scattering computer program, provided by K. L. Cashdollar of the Pittsburgh Mining and Safety Research Center, Bureau of Mines, produced calculations of $\overline{Q}_{\lambda}$ and the $\overline{Q}_{\lambda}$ ratios as a function of d_{32}. The program required as inputs the complex

refractive index of the particles, the refractive index of the surrounding medium, the standard deviation of the particle distribution and the wavelengths of light. During this investigation, the surrounding medium was assumed to be air with a refractive index of one. Because most of the exhaust particulate can be reasonably assumed to be carbon, the program was supplied with estimated values for the complex refractive index and the standard deviation of carbon particles [Ref. 8].

Using three transmittance ratios, three values of d_{32} are obtained. If all three d_{32} values were not nearly identical, the complex refractive index and/or the standard deviation chosen were not correct. Once $\overline{Q}_\lambda$, d_{32}, and T_λ were known, mass concentration could be calculated with the following rearrangement of equation (6):

$$Cm = -\frac{2}{3}\left[\frac{\rho d_{32}}{\overline{Q}_\lambda L}\right] \ln T_\lambda \qquad (8)$$

E. EXTRACTIVE AND THERMOCOUPLE PROBE SAMPLING SYSTEMS

The extractive sampling probe used in this investigation and the associated sampling system were adapted from the design used by Samuelson, et. al. [Ref. 10]. The probe was constructed of stainless steel and was water cooled in order to withstand the heat and erosive environment of the combustor. Included in the probe design were two isokinetic pressure ports, the primary

particulate sampling line, a gas sampling port, and an inert gas injection port. The isokinetic pressure ports were connected to a pressure transducer and monitored to insure that the gas velocity entering the probe was nearly identical to that in the combustor. The purpose of the inert gas injection port was to dilute the mixture, quench reactions, and prevent deposition along the walls. A schematic of the probe is shown in Figure 17. The dimensions of the probe presented in the schematic were the smallest reasonable size to incorporate the necessary ports and to provide clearance for the sample. Because of the relative size of the combustion chamber to that of the probe, blockage was not considered to be a significant problem.

A photograph of the probe is presented in Figure 18. The stainless steel tube extending from the bottom of the probe served as the water return line and also as a guide for positioning of the probe within the combustor. The probe could be positioned at any axial location within the combustor during the run. Figure 7 shows the probe and its insertion point into the combustor. The probe's relative positioning inside the combustor for this investigation is shown in Figure 2. The water supply reservoir and pump are shown in Figure 19. The sampling lines and water entry tubes were protected from the exhaust stream by a support stand attached to the rear of the probe.

The remainder of the system consisted of a heated sample line leading from the probe to an oven (Figure 20). The line was heated to prevent condensation. The oven, heated to 80^{o}

centigrade, contained a two stage filter utilizing 47 mm Nuclepore membrane filters: $8_{\mu m}$ pore size for the primary filter and $0.2_{\mu m}$ pore size for the secondary. Nuclepore filters were chosen for their adaptability for viewing with a scanning electron microscope (SEM). A schematic of the entire extractive probe sampling system is shown in Figure 21 [adapted from Ref. 10].

The stagnation thermocouple probe was built to the exact same dimensions as that of the extractive probe. The pressure ports, the inner gas port, and the sample gas port were not needed for this probe. A chromium-alumel thermocouple was utilized during the initial testing and was placed along the centerline of the probe. The purpose of this apparatus was to provide an axial temperature plot for each test, in order to evaluate the overall effect of the various fuel additives used. The thermocouple probe was mounted in the same location as the extractive sampling probe.

F. TEST CELL INSTRUMENTATION AND DATA COLLECTION

The test cell was instrumented in such a manner as to permit the monitoring of critical test temperatures and pressures. Using standard ASME flow calculations [Ref. 7], mass flow rates anywhere within the test cell could be calculated. Permanent records were kept only for those pressures deemed critical to the analysis of test data.

A Honeywell 1508 visicorder recorded the test air pressure upstream of the sonic choke for mass flow determination, the change in pressure across the fuel nozzle for fuel flow determination, and the combustion chamber pressure during testing. In addition to these recordings, the visicorder recorded a 5 Hz signal at the bottom of each trace that served as a time reference for test reconstruction. Other temperatures and pressures critical to test cell operation were monitored continuously during a test run by the control room personnel. Because several test cell parameters required manual adjustments from within the test cell during a test run, the in cell operator was equipped with the necessary instrumentation to monitor those items. Specifically, the differential pressure as seen by the isokinetic pressure ports from within the probe was continuously displayed on a digital voltmeter within the cell. In addition, the pressure within the combustion chamber and within the aft closure were displayed by two gauges within the test cell to allow manual adjustment of the variable exhaust nozzle when needed. All flow readings required to run the gas sampling system were located inside the test cell. All other flow readings were available on the control room instrument panel.

For the purposes of this investigation, the optical transmission data were recorded using three strip chart recorders. The outputs of the optical systems were directly attached to the recorders to provide a permanent, real time recording of the transmissivity within the combustor and at the engine

exhaust. In future testing, the data acquisition and processing will be accomplished by an existing HP data acquisition and processing system. Samples of the combustion particulate matter were collected by the extractive probe system and analyzed using a SEM. This redundant data collection technique served to verify the results obtained by the optical system.

G. NITROGEN OXIDES ANALYZER

A Monitor Labs, Model 8440 E, Nitrogen Oxides Analyzer, was installed to determine NOx production during engine operation. Although this apparatus was not utilized during this initial investigation, it will be used extensively in future tests to determine fuel additive effects on NOx production.

III. EXPERIMENTAL PROCEDURE

Before conducting a test, it was essential to insure that all data collecting equipment was turned on and warmed up. Thirty minutes were generally considered to be adequate.

The same amount of time also served to eliminate unwanted condensation from the optical detection equipment. While the electrical equipment was warming, other preliminary test set up tasks (such as filling fuel tanks, turning on main air, and setting associated gas pressure equipment) were accomplished.

After the initial warm-up period, the optical detector systems and the transmissometer were checked to make certain that the proper alignment had not been disturbed. The transmissometer was checked by verifying that zero and one hundred percent opacity reading could be realized. The optical detector system was checked by measuring the maximum detector outputs and comparing them to output data taken when the system was first installed and aligned. The probe sampling system was readied by warming the sample oven to 80 degrees centigrade, turning on the probe line heater element and determining that the water cooling system was operating and that all air bubbles had been eliminated. Finally, the test cell pressure transducers and the associated recording equipment were calibrated using a hydraulic dead weight tester.

When all test equipment had been satisfactorily set and calibrated, the test cell was readied for the test to be conducted by setting the appropriate test cell pressures. The control room operator was responsible for setting the desired main air flow rate, fuel flow rate, and the oxygen and ethylene flow rates for the vitiated air heater operation. Using the calibration charts in the control room and the hand loading valves on the control panel, the cell was prepared for the test run.

Once the combustor ignition sequence was completed, the in cell operator could fine adjust the exhaust nozzle aperture, if needed, to achieve the proper back pressure. It was also his task to adjust the flow through the sampling system to successfully zero the differential pressure between the probe isokinetic pressure ports. When steady state outputs were achieved, a particulate sample and data were taken.

The purposes of this investigation were (1) to verify proper test cell operation and the adequacy of the instrumentation and (2) to compare the optical and sampling probe data used for determination of particulate size. To do this, values for fuel nozzle pressure drop, main air pressure, and combustion chamber pressure were recorded. For this initial investigation, the fuel additive pumps were not operating. JP-4 data, alone, sufficed to verify test cell operation. When steady state operating conditions were achieved, a particulate sample was

collected. After data collection was completed, and the engine had been shut down, post-run transmissometer zeroes and one hundred per cent points were marked on the strip chart recordings to ensure that alignment of the optical measuring equipment had not changed.

IV. RESULTS AND DISCUSSION

A. INTRODUCTION

The main purposes of this investigation were (1) to test and verify the required operation of the T-63 gas turbine combustor as modified for use in this test cell, (2) to evaluate the adequacy of the data collection equipment, and (3) to compare the particulate size data obtained using the sampling probe and the optical system. A series of four tests were conducted between 15 June 1983 and 20 June 1983. The tests were completed using commercial JP-4, and the combustor was operated at approximately 75% of normal rated conditions as specified by the manufacturer.

The data collected during this investigation, as well as the associated engine operating conditions, are summarized in Tables I and II. A sample Mie scattering chart is presented in Figure 22. This type of chart is required to determine the particle sizes as detected by the collimated white light equipment. SEM photographs of exhaust particulate collected during run one of the series are shown in Figures 23 - 27.

It should be remembered that this series of tests was conducted in an effort to identify any test cell operational or data collection deficiencies. As such, the data presented should be analyzed for trends. The lessons learned from the data will be used to improve the apparatus for future tests.

B. GAS TURBINE COMBUSTOR TEST CELL OPERATION

By attempting to run each test at the same operating condition, it was hoped to verify that the combustor could be run at any desired setting and that those conditions could be reproduced at a future time. The data presented in Table I indicates the operating conditions achieved during the test runs.

As described earlier, the air flow through the combustor was regulated by means of a dome pressure regulator that could be adjusted inside the control room. The air flow rates achieved during the runs did not vary by more than .09 lbm/sec, or approximately 3%. This was achieved without fine adjusting the dome pressure during the run. The set pressure for the dome was calculated using the following equation for sonically choked flow of an ideal gas through a flow nozzle:

$$\dot{m}_a = .1315 \frac{P_t}{\sqrt{T_t}} \qquad [\text{lbm/sec}] \qquad (9)$$

A thermocouple located within the air supply line provided the needed temperature. The data presented suggests that the air flow could be adequately set utilizing the existing apparatus.

The T-63 fuel nozzle was calibrated by measuring mass flow over timed intervals for different pressure differentials. The resulting calibration is equation(3). During a test, fuel flow was controlled by varying the nitrogen pressure level

within the fuel tank. The desired tank pressure was determined by using equation (3) together with the estimated combustor pressure. Some difficulty was experienced in maintaining a constant fuel tank pressure during initial runs. This, in turn, caused some fluctuation in the fuel air ratio (f). The data, however, indicated that it was possible to achieve a desired fuel air ratio with the control apparatus as designed. The replacement of some of the fuel tank pressure regulating equipment should eliminate the fluctuation problem.

It was evident that the test cell control apparatus was sufficient to provide any desired test cell operating condition, allowing several tests to be conducted with the same operating conditions. This is, of course, essential for conducting fuel additive research.

C. EXTRACTIVE PROBE SAMPLING SYSTEM

The extractive probe sampling system used during this investigation was adopted from the design used by Samuelsen, et. al. [Ref. 10]. While this water cooled probe design proved sufficient for Samuelsen's purposes, it was unknown whether or not it would survive the T-63 combustor environment. Significant differences existed between the types of combustors being tested; for example, the average velocity within the combustor and the presence of liquid fuel droplets. The purpose of these tests was to determine if the sampling probe could survive the new environment, and if a representative particulate sample

could be obtained with the nuclepore filter system. For these initial tests, a water heater was not employed for the probe cooling water.

The extractive probe was placed in the combustor so that the head of the probe was at the rear of the combustion chamber. This insured that the probe was well clear of the primary combustion zone, and that the least severe conditions possible were experienced by the probe during these initial tests. After the combustor was running at steady state conditions, the in-cell operator insured that isokinetic conditions were achieved by adjusting the flow rate pulled into the probe. When this was accomplished, the three way valve (Figure 17) was electrically actuated, and a sample was taken for four minutes.

SEM photographs were taken of both sampling filters. Two different preparations were employed, gold coating and aluminum coating, as indicated on the photographs. In addition, two different SEM's were utilized: a Cambridge S4-10 and a Hitachi S540. Both SEM's and both coating methods produced similar results. Figure 23 is a relatively low magnification photograph of the primary filter ($8_{\mu m}$). This figure shows a number of large agglomerations. Figures 24a and b show that these structures are puff like in nature and significantly larger ($30_{\mu m}$ to $50_{\mu m}$) than the pore size of the filter. This observation was not totally unexpected. In the study conducted by Samuelsen et. al., it was observed that when the sample rate was increased or when the N_2 dilution was reduced, puff like structures occurred.

The sample rates of this experiment were significantly higher than those of Samuelsen ($\bar{V}$=22 mps vice 15 mps). Also, N_2 dilution was not used during this initial test. At higher magnifications (Figures 25a and b), individual particles of particulate matter can be seen between the puff like structures. These particles vary in size, but generally lie within the range of $.25_{\mu m}$ to $.75_{\mu m}$.

The sample collected by the secondary filter ($.2_{\mu m}$), can be seen in Figures 26 and 27. In Figure 26, it should be observed that the filter is virtually saturated by the sample. A higher magnification (Figure 27a and b), however, reveals that some individual particles can be observed. At a maximum possible magnification of 40,000, the few individual round particles measure within the range of $.5_{\mu m}$ to $2.0_{\mu m}$.

The extractive probe sample results raised several questions. First, were the puff like structures on the primary filter actually present in similar form within the combustion chamber or were they probe collection induced agglomerations of the smaller particles? Second, what effects would occur on the sample from heating the cooling water and/or using dilution (N_2) [per Ref. 10]. Finally, what effects would result from decreasing the sample time?

Several observations and speculations can be made from the analysis of the samples. It is obvious that the sample time used for this initial test was too great. Both filters were saturated with sample matter to the point of restricting the

sample flow. The flow restriction was observed by the in-cell operator after approximately 30 seconds of sample time. At this point, isokinetic conditions were impossible to achieve. The quantity of sample matter collected made quantitative analysis of the sample difficult. It is speculated, based on the results printed in Reference 10, that the exclusion of the heated probe cooling water and the N_2 dilution significantly affected the results seen on the secondary filter. The plate-like formations seen in Figure 27a are indicative of water condensation [Ref. 10]. The nature of the sampling system (i.e. - bends in the sample line, etc.) will cause some agglomerates to form from individual particles. However, this problem can be minimized by quenching the sample and heating the cooling water. Finally, during the test, the probe was observed to have moved aft approximately 1.5 inches. This was caused by the force of the exhaust jet on the probe. The possible result of this movement was the blockage of the external pressure port by the probe guide inside the combustor. This would make the monitoring of the isokinetic pressure transducer useless. A more reliable probe positioning method is, therefore, recommended.

While some questions remain about the sample extracted during this test run, it is obvious that the extractive probe sampling system operated effectively throughout the test. The probe proved that it could withstand the environment of the T-63 combustor. Future tests will evaluate the probe when located within the primary combustion zone.

D. OPTICAL MEASUREMENTS

As discussed earlier, the primary purpose of the collimated white light sources and the three-frequency light detection units was to optically determine the size and concentration of the particulate matter. This was to be done at a position inside the combustion chamber, as well as at the engine exhaust. The opacity of the engine exhaust was also monitored continuously throughout the run.

The optical data extracted during each of the four runs are presented in Table II. The exhuast opacities are presented in Table I. It was not possible in these initial tests to determine d_{32} or Cm from the transmissivities provided by the optical equipment.

The transmissometer located at the engine exhaust provided a fairly consistent opacity reading of approximately 7% throughout the test runs. This opacity is quite small and indicates that the engine burns extremely clean. In the same manner as the transmissometer, the three frequency light detector at the exhaust gave consistently high readings of transmissivity. Because the transmissivities were all very high, the extinction coefficient ratios could not be accurately determined. Small changes in high transmittance values greatly effect the log ratios. In other words, the sensitivity of the optical technique used at the exhaust was insufficient for use with such a clean burning engine. To obtain meaningful data at the

exhaust, the engine must either be run with higher exhaust gas opacity (i.e., a more fuel rich setting), or more of the exhaust gases must be directed past the light detection equipment.

Problems of a different nature were experienced with the optical unit located in the combustor. During a preliminary run on the engine, it was discovered that two of the wavelengths used (i.e., 4500 and 10140 angstroms) were saturated by light produced by the combustion process. 10140 angstroms lies within the IR range and 4500 angstroms is in the blue light range. For the test runs, the 4500 angstrom filter was replaced with a 5145 angstrom narrow pass filter. Both the 5145 and the 6500 angstrom wavelengths produced excellent transmissivity data (Table II). The problem, however, resulted from the closeness of the two wavelengths and the elimination of the data for the third wavelength. The extinction coefficient ratios produced from the transmissivity data (Table II) were consistently below the Mie scattering curve (Figure 22). Because the two wavelengths were so close, the accuracy of the transmittance ratios also suffered. Therefore, it was apparent that, for future testing, three new frequencies must be used to produce reliable data. A 3000 angstrom and an 8500 angstrom filter will be used in conjunction with the 5145 angstrom filter in future tests.

The nature of the data produced by the light source looking through the combustor and that produced by the extractive probe led to some speculation. The SEM photographs showed that many

of the particles produced in the combustion chamber were within the range of $.25_{\mu m}$ to $2.0_{\mu m}$. While the extinction coefficient ratio produced by the light source did not allow direct d_{32} determination from the charts, they did indicate a trend. Looking solely at the low portion of the 6500-5145 curve (Figure 22), it is apparent that the range of d_{32} is from $.05_{\mu m}$ to $.2_{\mu m}$. In addition, the trend of low extinction coefficient ratios further implies that a complex refractive index of 1.8 - .30i and a standard deviation of a 1.5 will probably be most suitable for use in data reduction. All of this, of course, is only speculation and further testing using the three new light frequencies in the detector is required.

V. CONCLUSIONS AND RECOMMENDATIONS

This test series was conducted in order to evaluate the performance of the gas turbine combustor test apparatus at the Naval Postgraduate School. Test cell control instrumentation and data collection techniques were analyzed for consistency of operation and accuracy of results. The adequacy of the test cell apparatus was evaluated and the principle results and recommendations are summarized as follows:

(a) The T-63 combustor operated reliably throughout this test series. No equipment malfunctions were experienced. It is recommended that a new fuel pressure regulation system be developed and installed to eliminate the fuel flow fluctuation problem.

(b) The extractive probe sampling system also operated reliably during the test. Movement of the probe during the test run must be controlled. The efore, it is recommended that a new positioning unit be designed which can better counter the exhaust jet force on the probe. It is further recommended that the sampling time used during a test be reduced to between 15 seconds and 30 seconds. This should alleviate some of the sample analysis problems experienced during this test series.

(c) The optical technique used to look inside the combustor appears to be capable of supplying reliable data. It

is necessary, however, to change two of the wavelengths used in the detector. 8500, 5145, and 3000 angstroms should provide the necessary frequency separation to allow reliable data to be obtained. The collimated light detection technique, on the other hand, does not appear to be adequate for use in the exhaust of this combustor during normal operating conditions. Routing more of the exhaust stream past the detector or running the combustor in a fuel rich mode may provide the needed opacity. Beyond this, a different optical technique may be more suitable to this particular exhaust environment.

Figure 1. COMBUSTOR TEST CELL

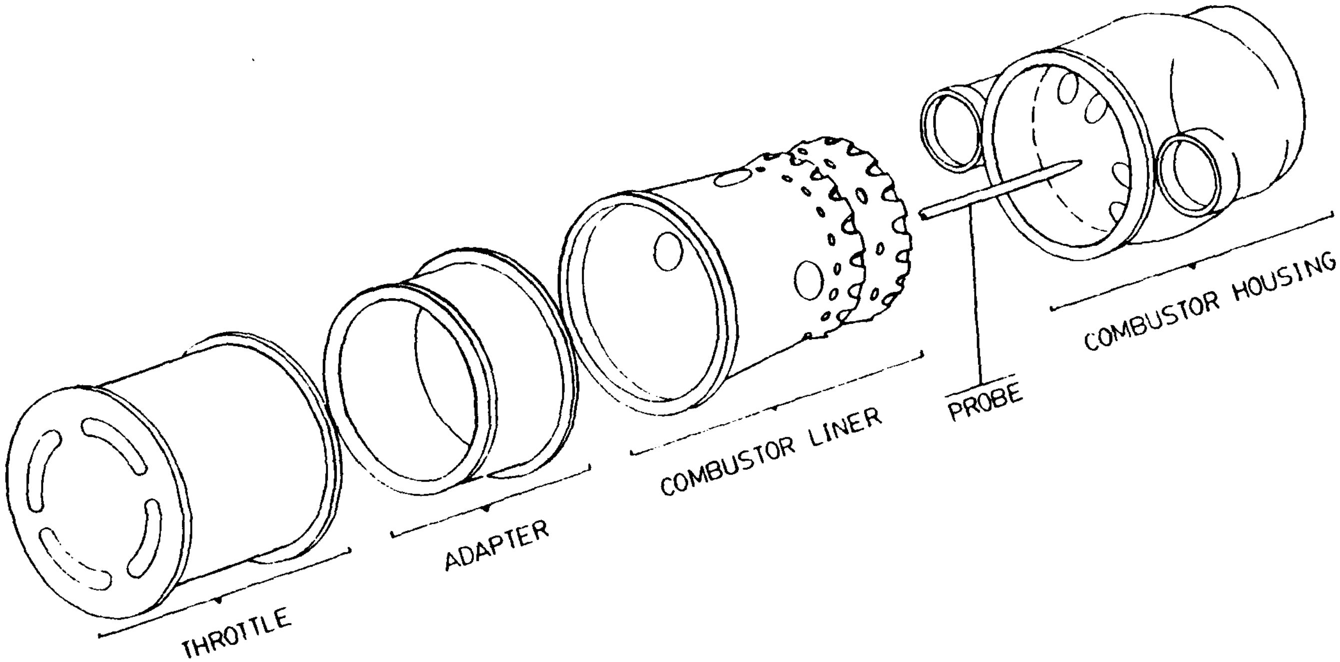


Figure 2. SCHEMATIC OF T-63 COMBUSTOR

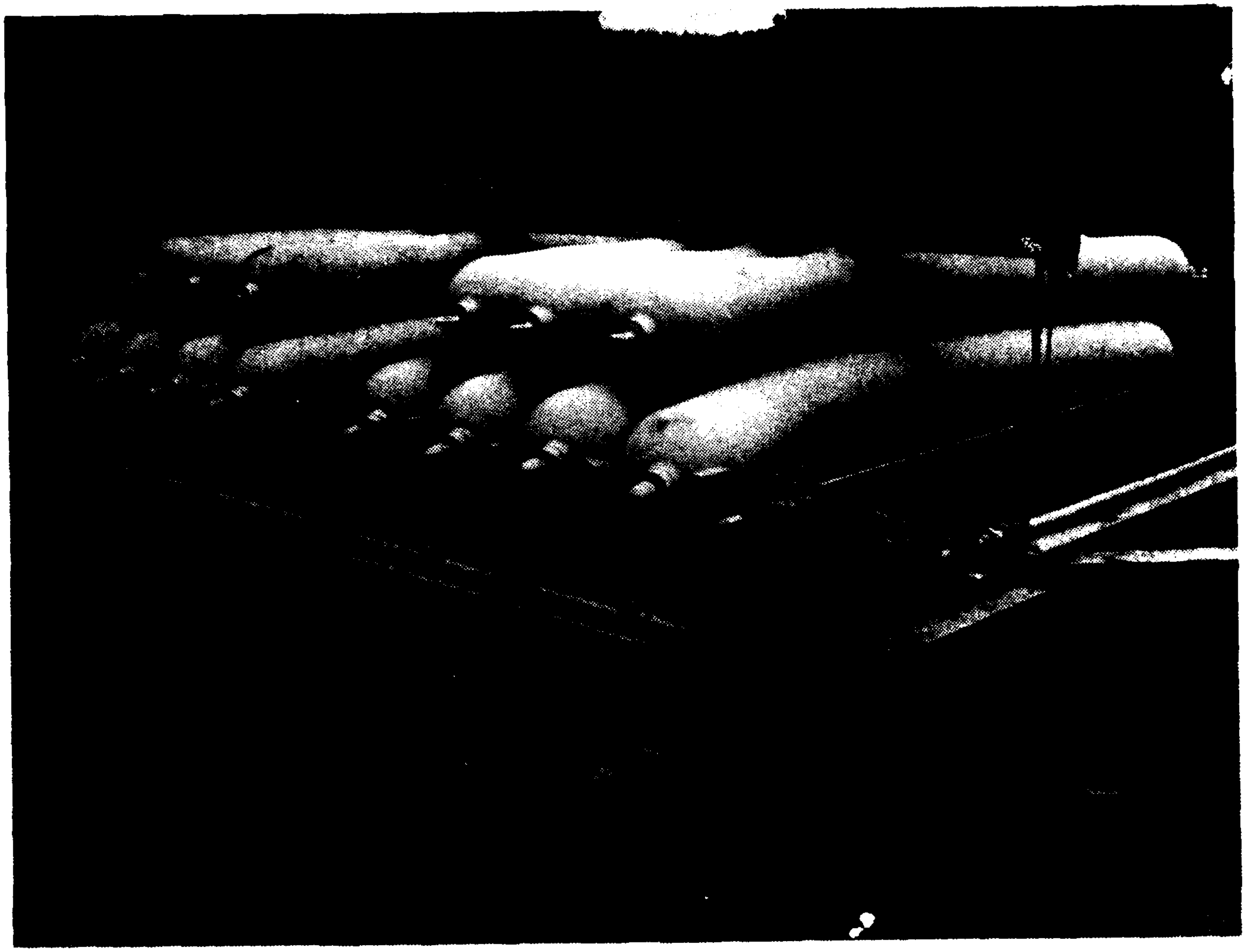


Figure 3. HIGH PRESSURE AIR RESERVOIR

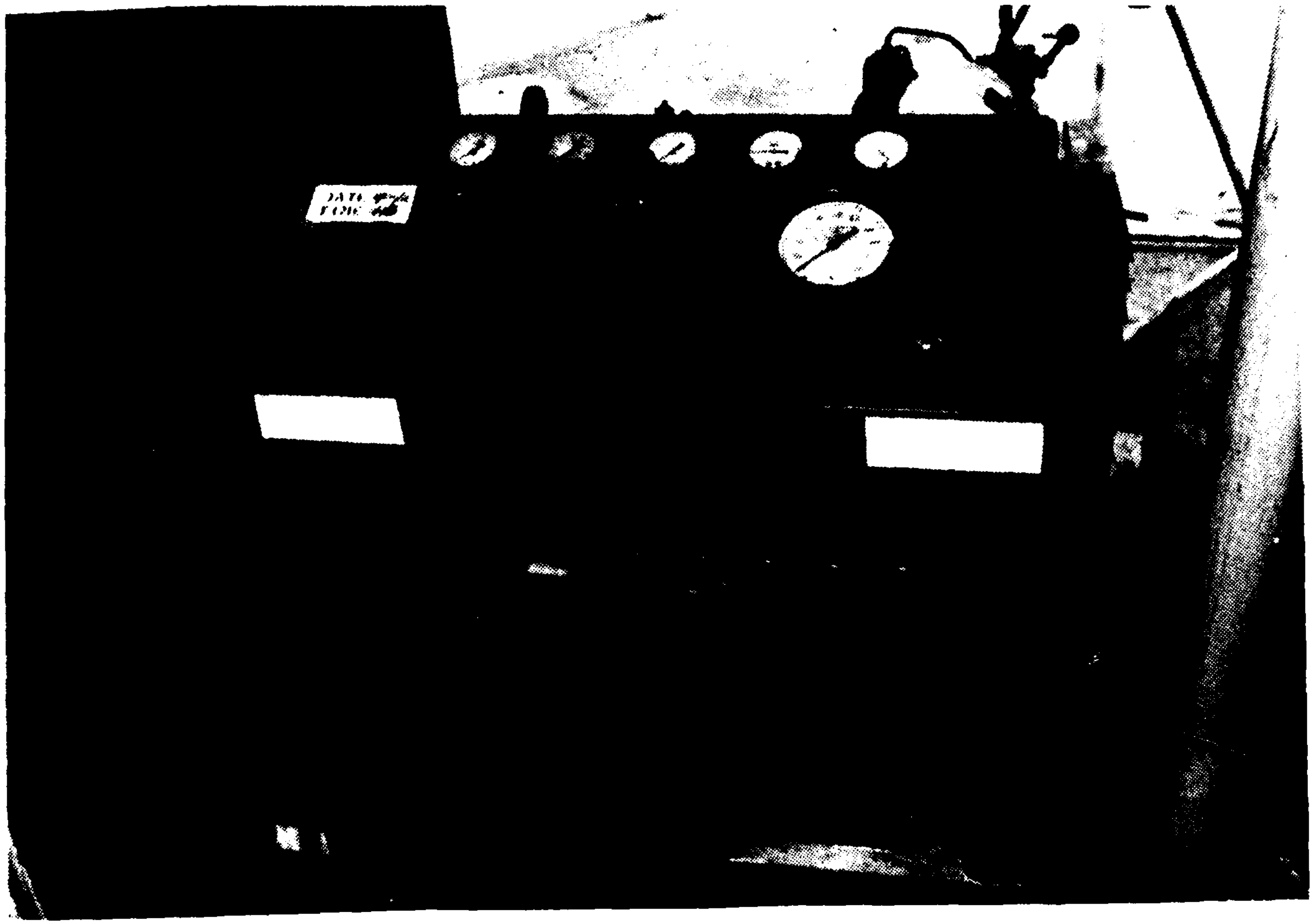


Figure 4. JOY COMPRESSOR

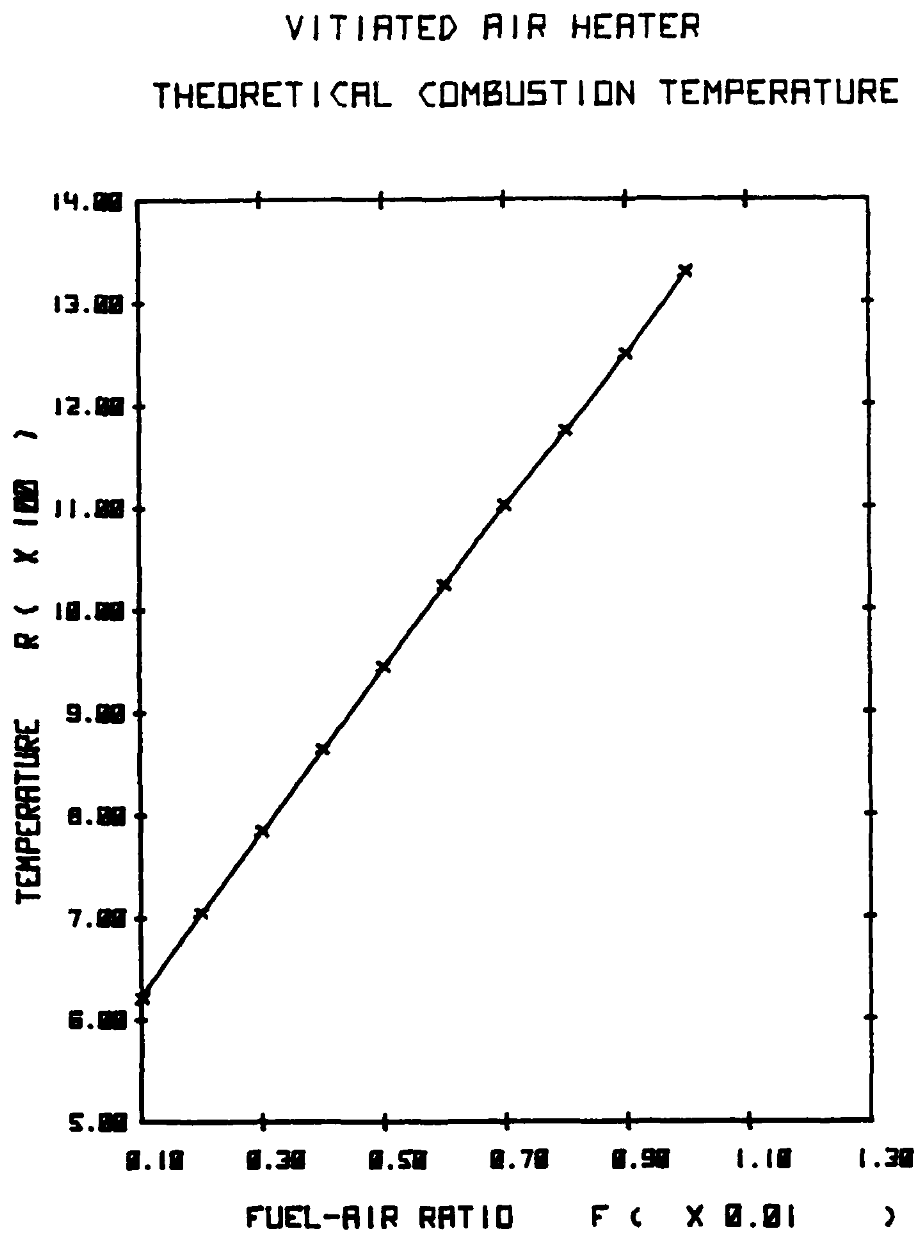


Figure 5. THE VITIATED AIR HEATER'S THEORETICAL COMBUSTION TEMPERATURE VS. FUEL TO AIR RATIO

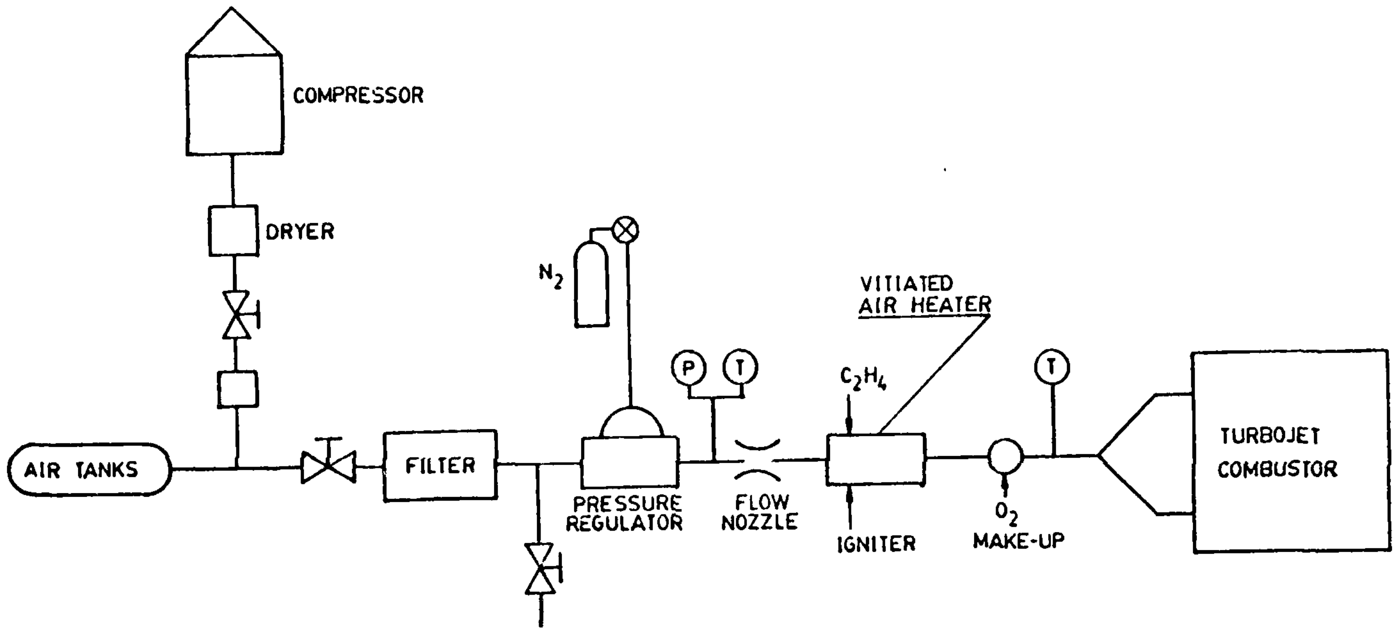


Figure 6. SCHEMATIC OF AIR SUPPLY SYSTEM

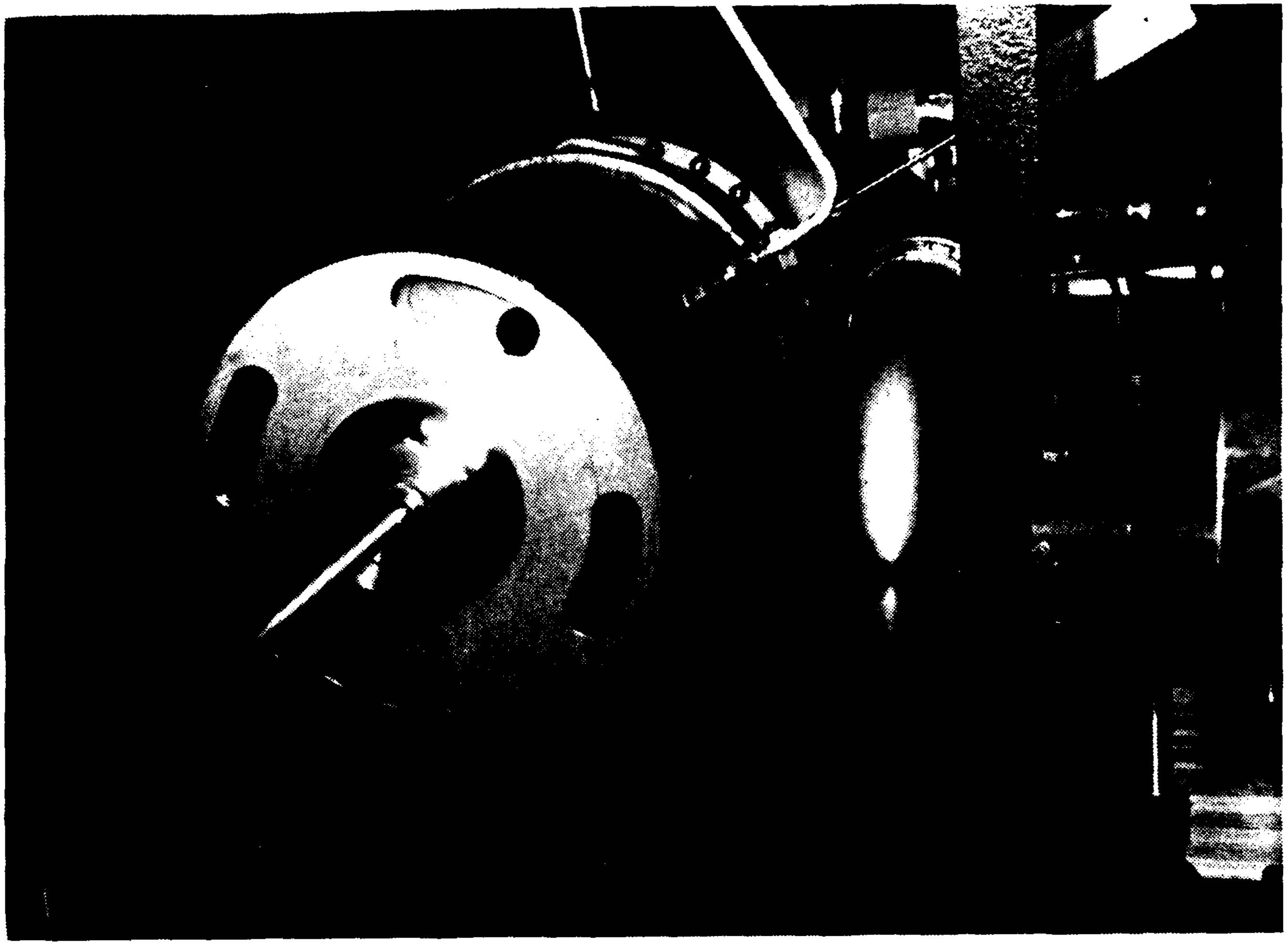


Figure 7. VARIABLE AREA EXHAUST EXIT

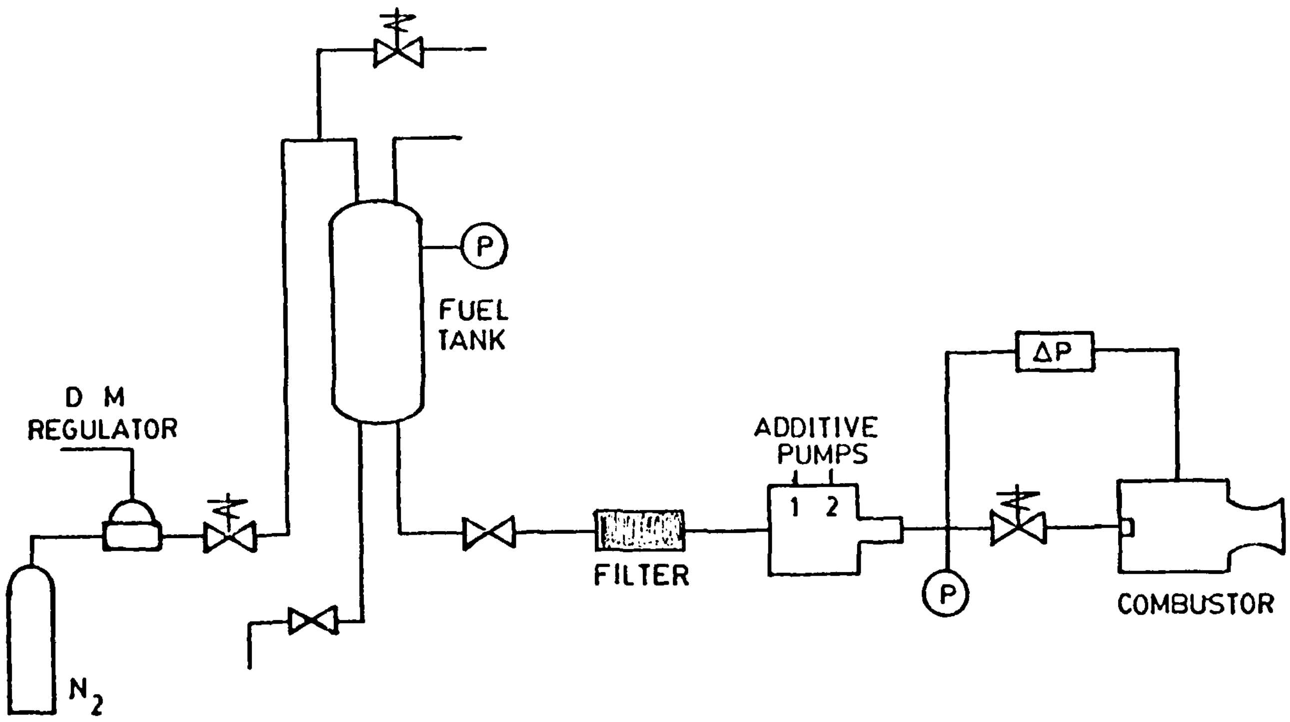


Figure 8. SCHEMATIC OF FUEL SUPPLY SYSTEM

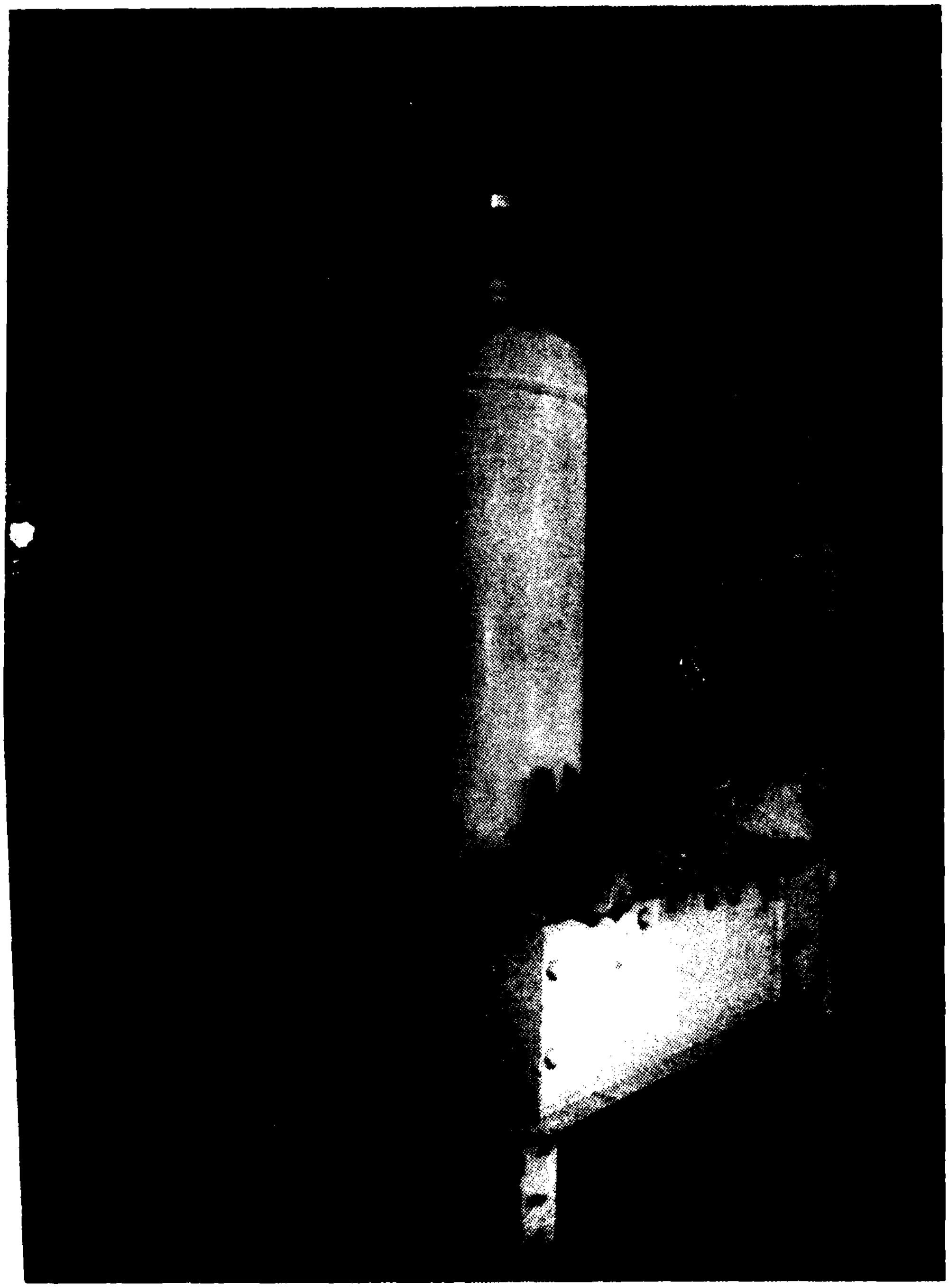


Figure 9. FUEL TANK

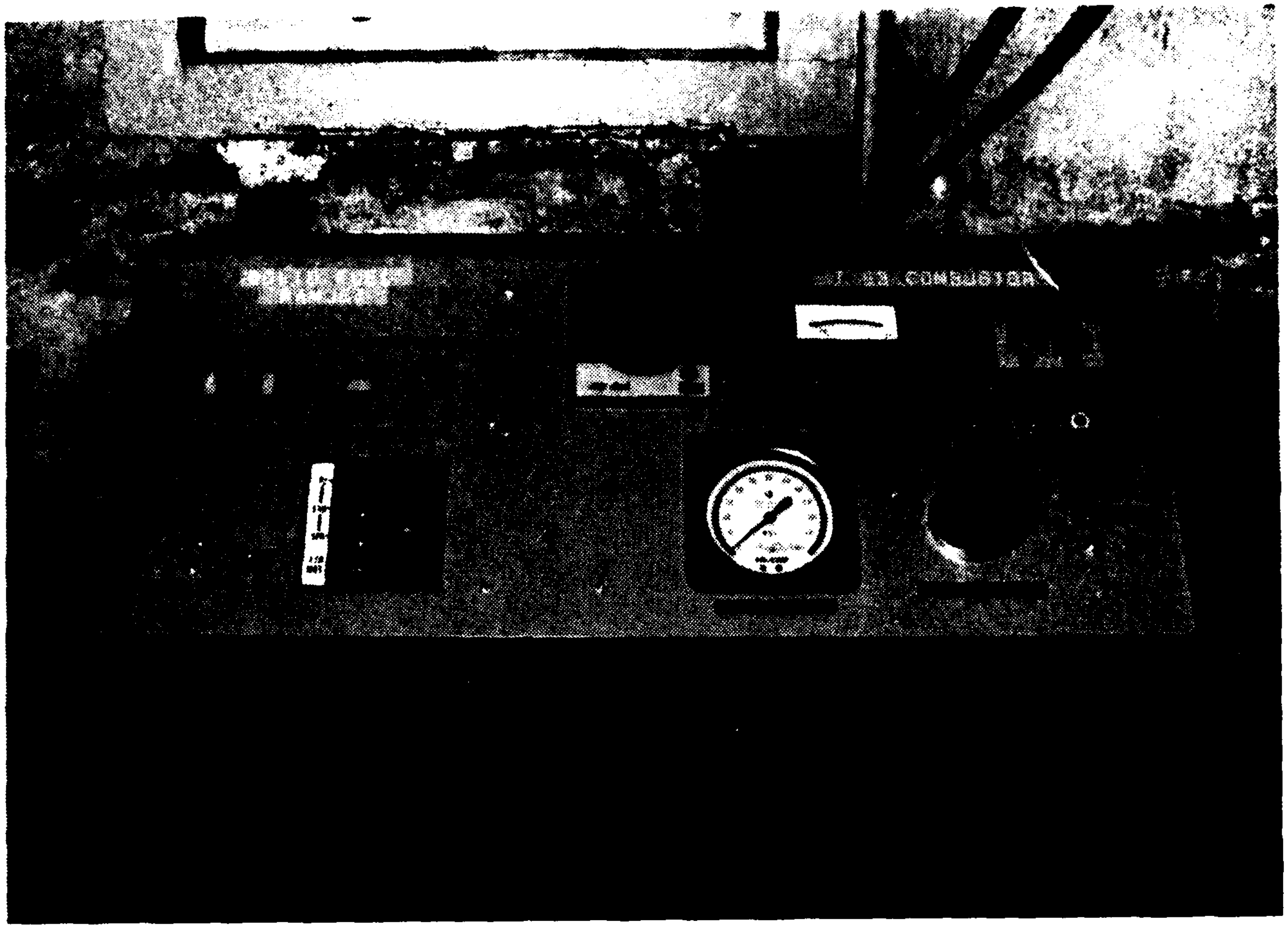


Figure 10. HAND OPERATED FUEL TANK PRESSURE REGULATOR

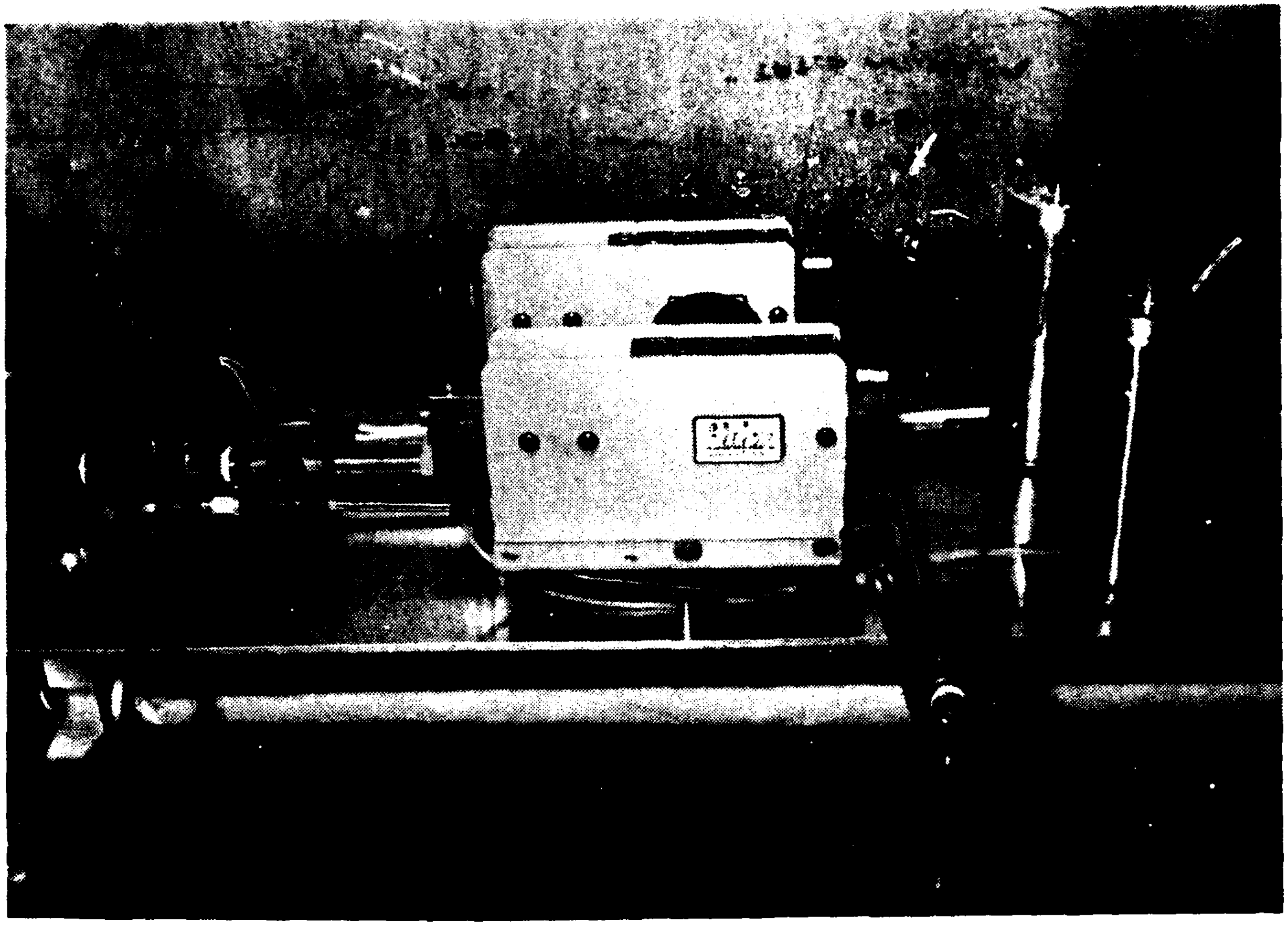


Figure 11. ELDEX, MODEL E, PRECISION METERING PUMPS

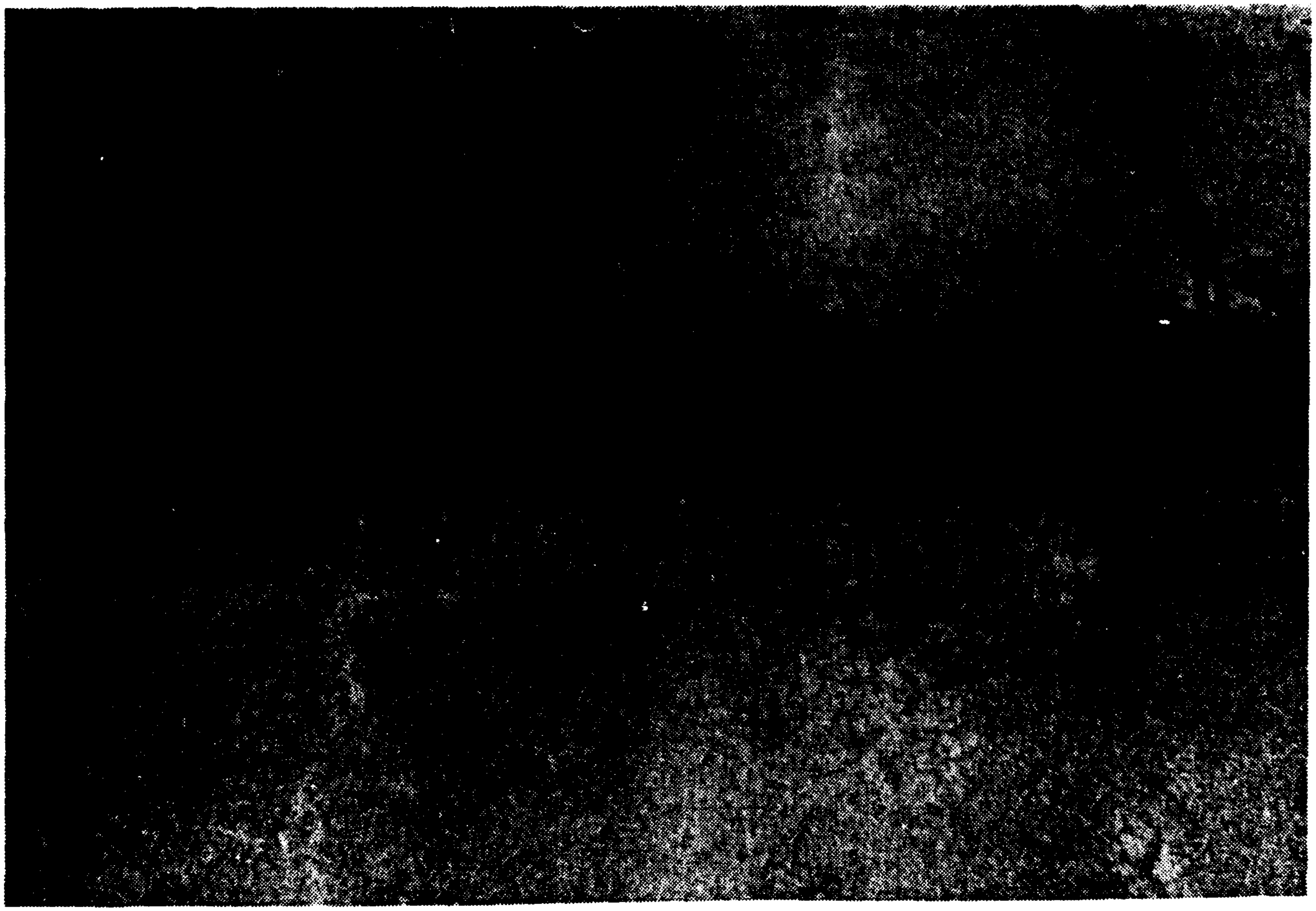


Figure 12. LEADS AND NORTHROP MODEL 6597 WHITE LIGHT SOURCE AND DETECTOR

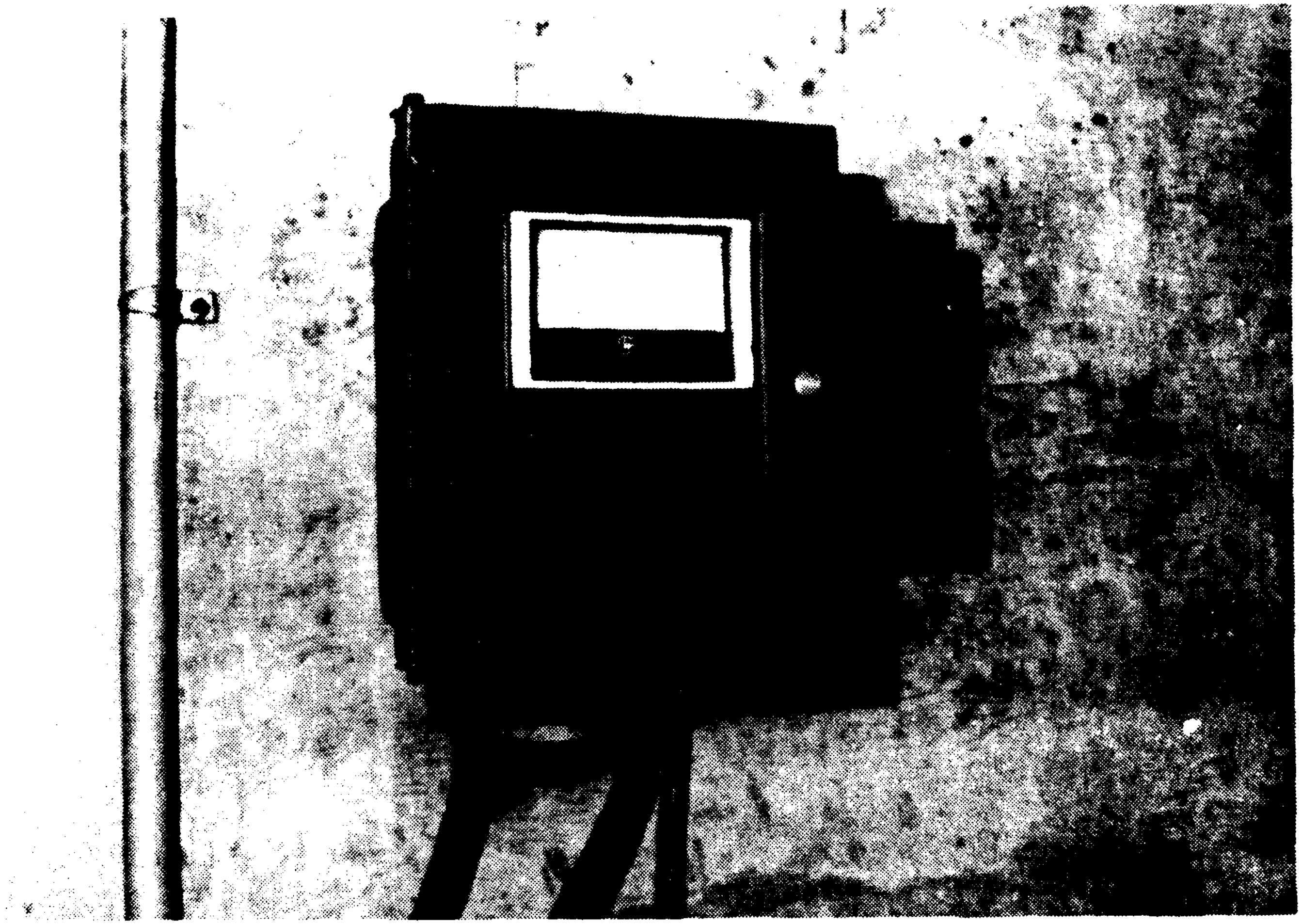


Figure 13. LEADS AND NORTHROP MODEL 6597 SIGNAL CONDITIONER/DISPLAY UNIT

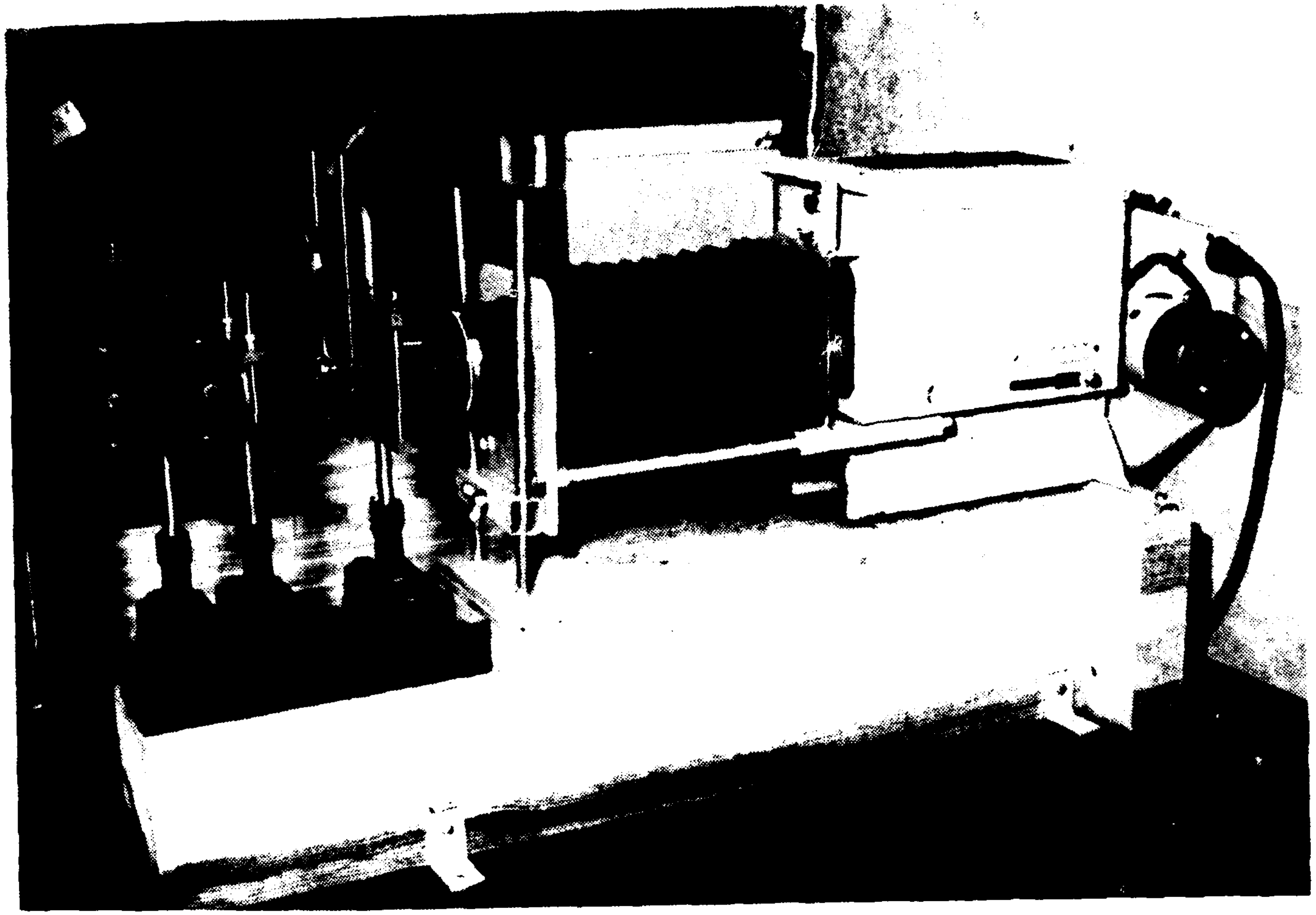


Figure 14. COLLIMATED WHITE LIGHT SOURCE

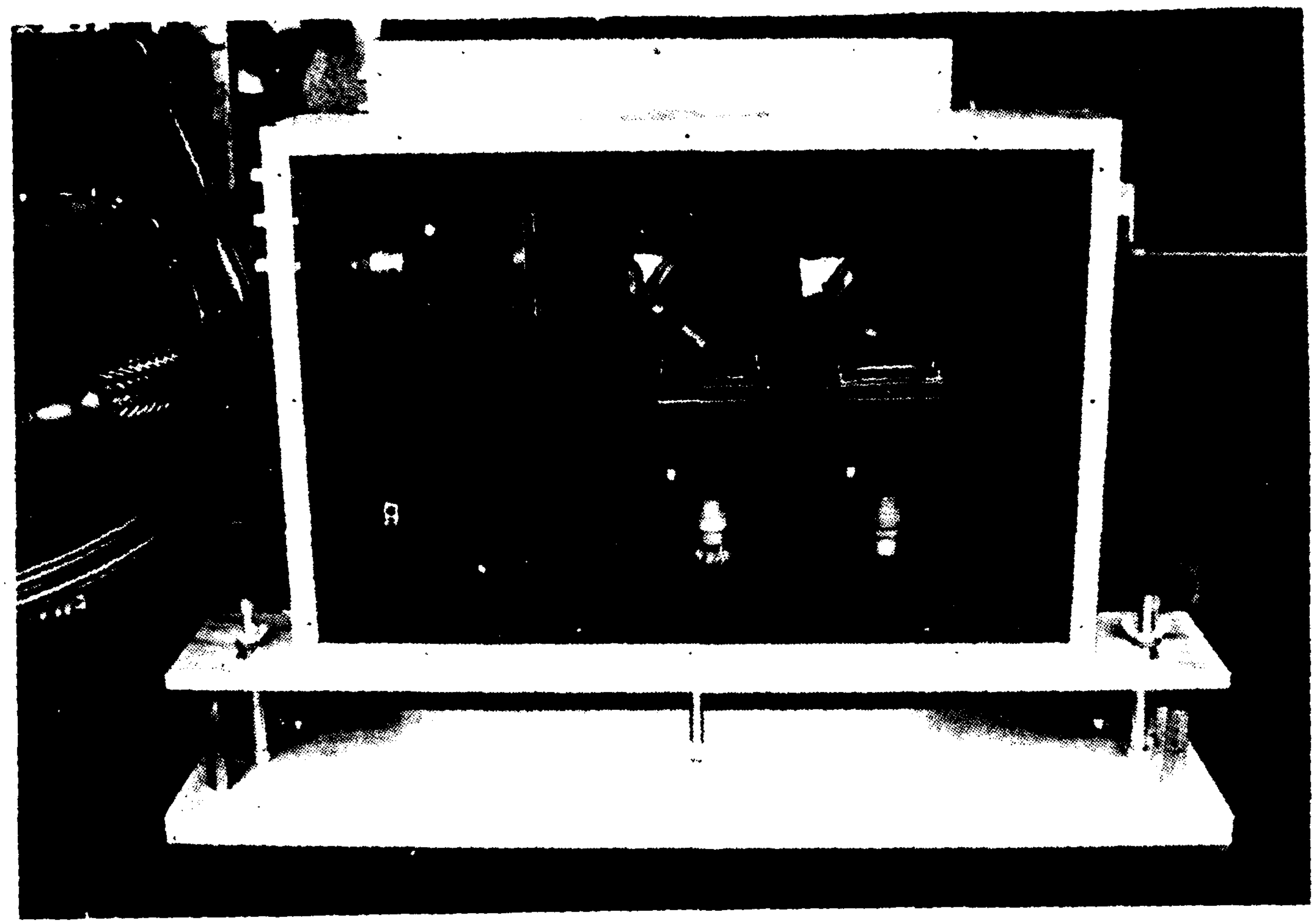


Figure 15. THREE FREQUENCY LIGHT DETECTOR

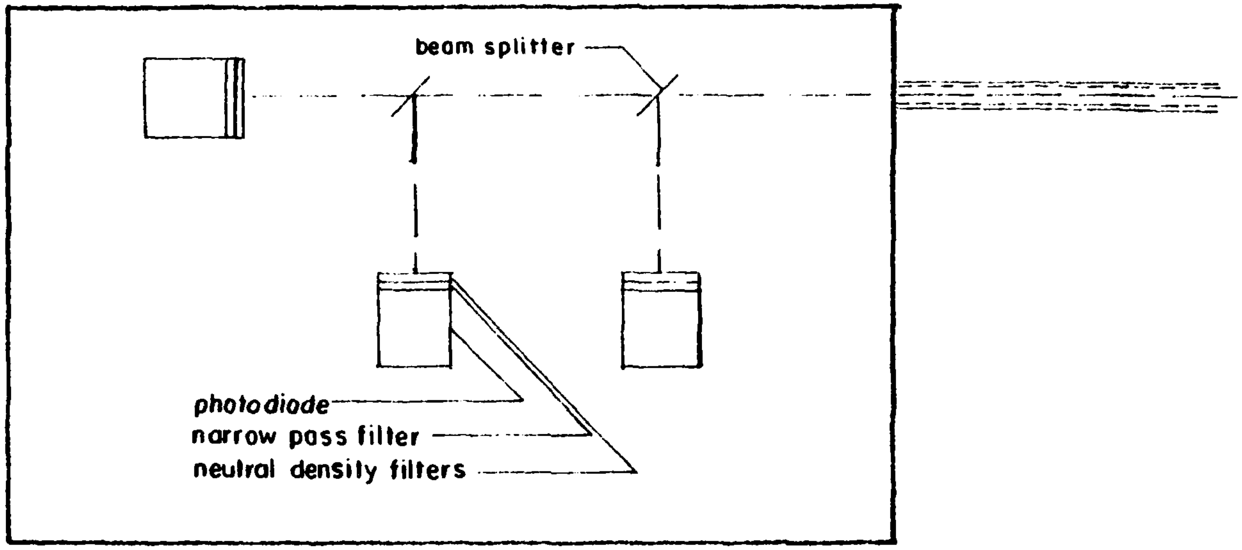


Figure 16. SCHEMATIC OF LIGHT PATH THROUGH THE OPTICAL DETECTOR

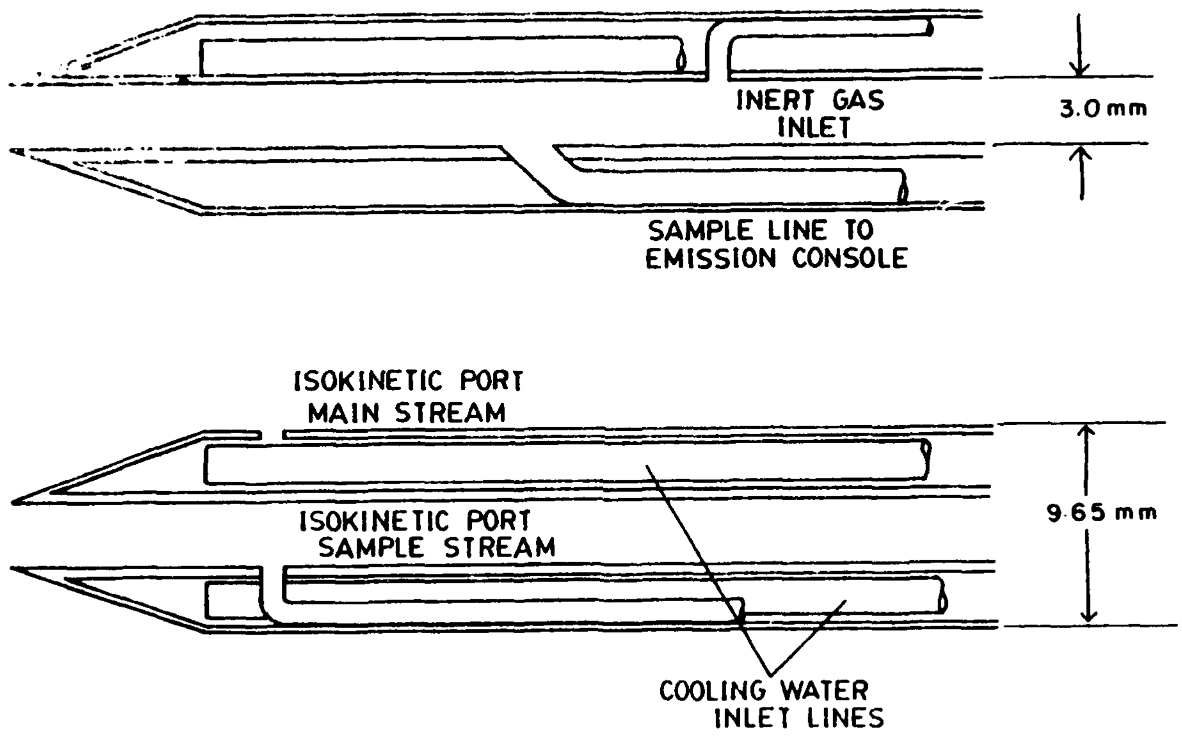


Figure 17. SCHEMATIC OF WATER COOLED EXTRACTIVE SAMPLING PROBE

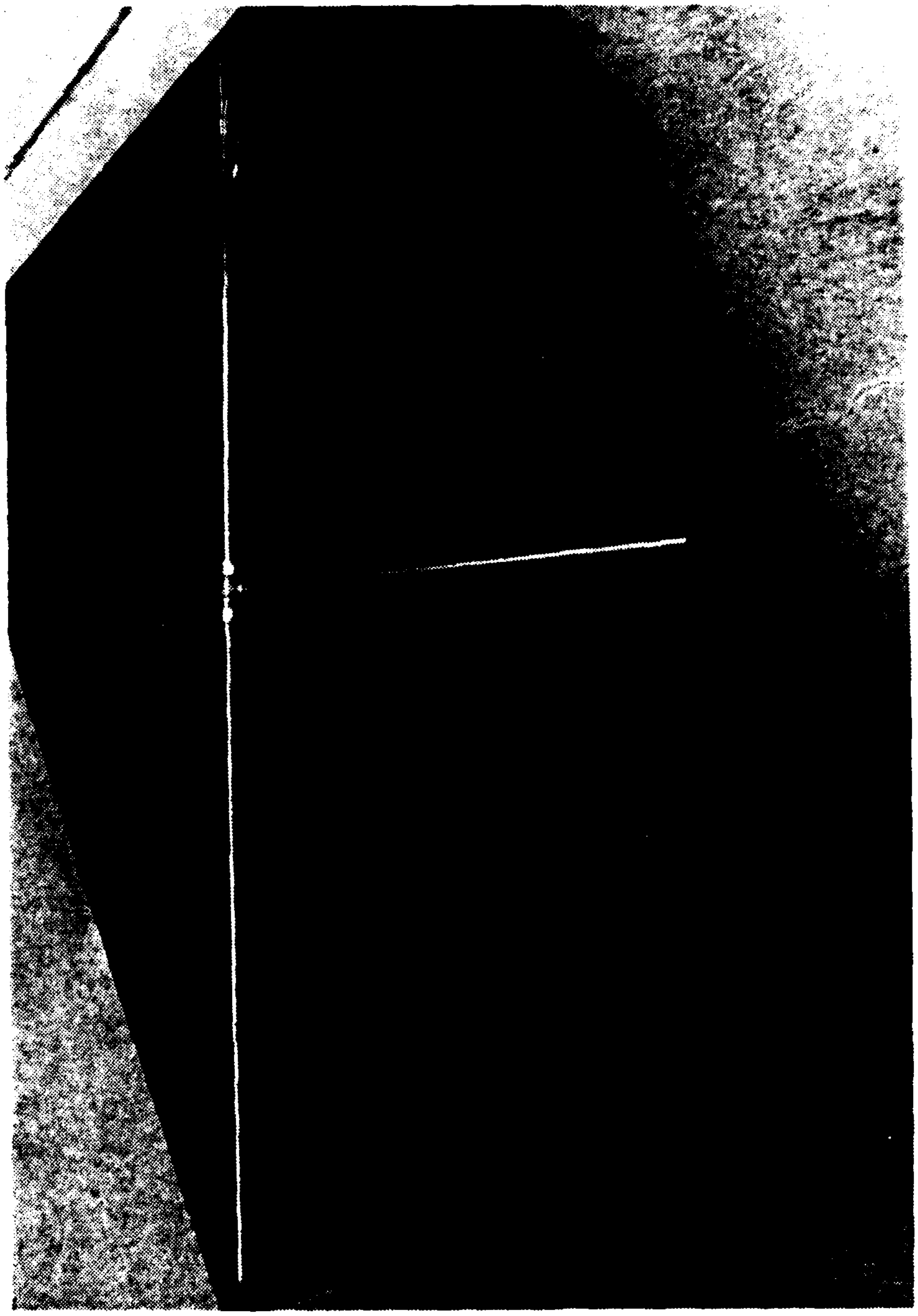


Figure 18. EXTRACTIVE SAMPLING PROBE

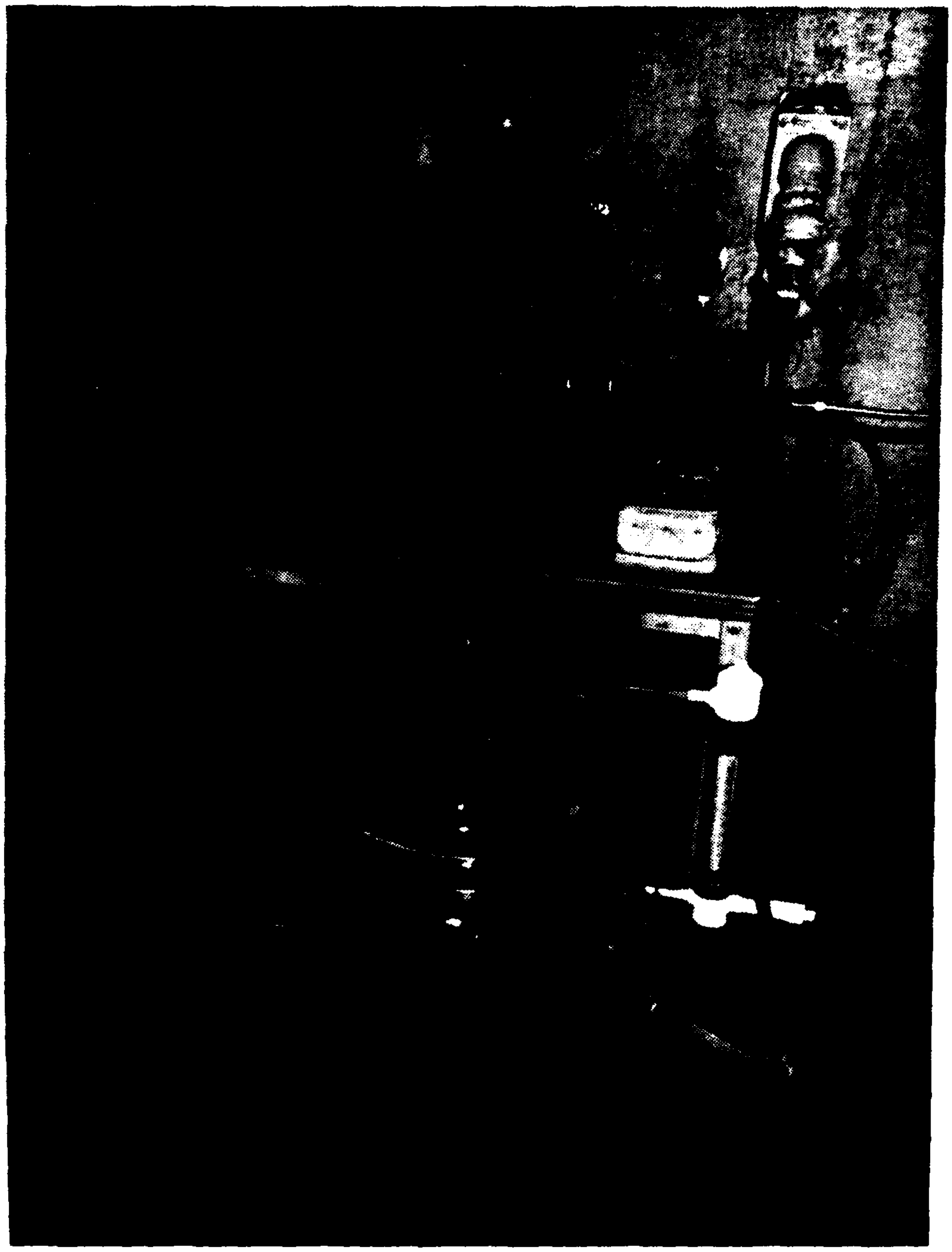


Figure 19. PROBE WATER SUPPLY SYSTEM

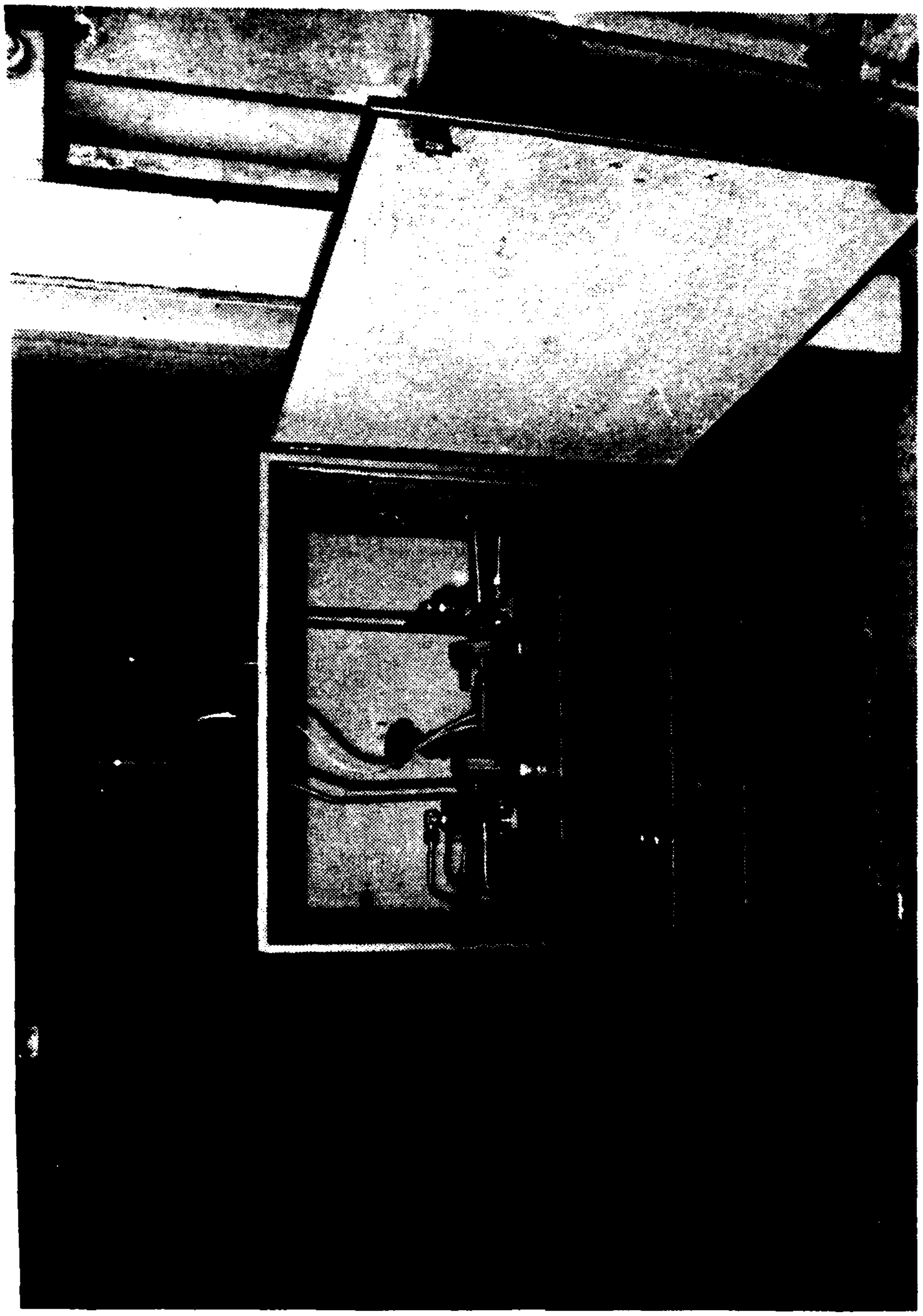


Figure 20. SAMPLE OVEN AND FILTERS

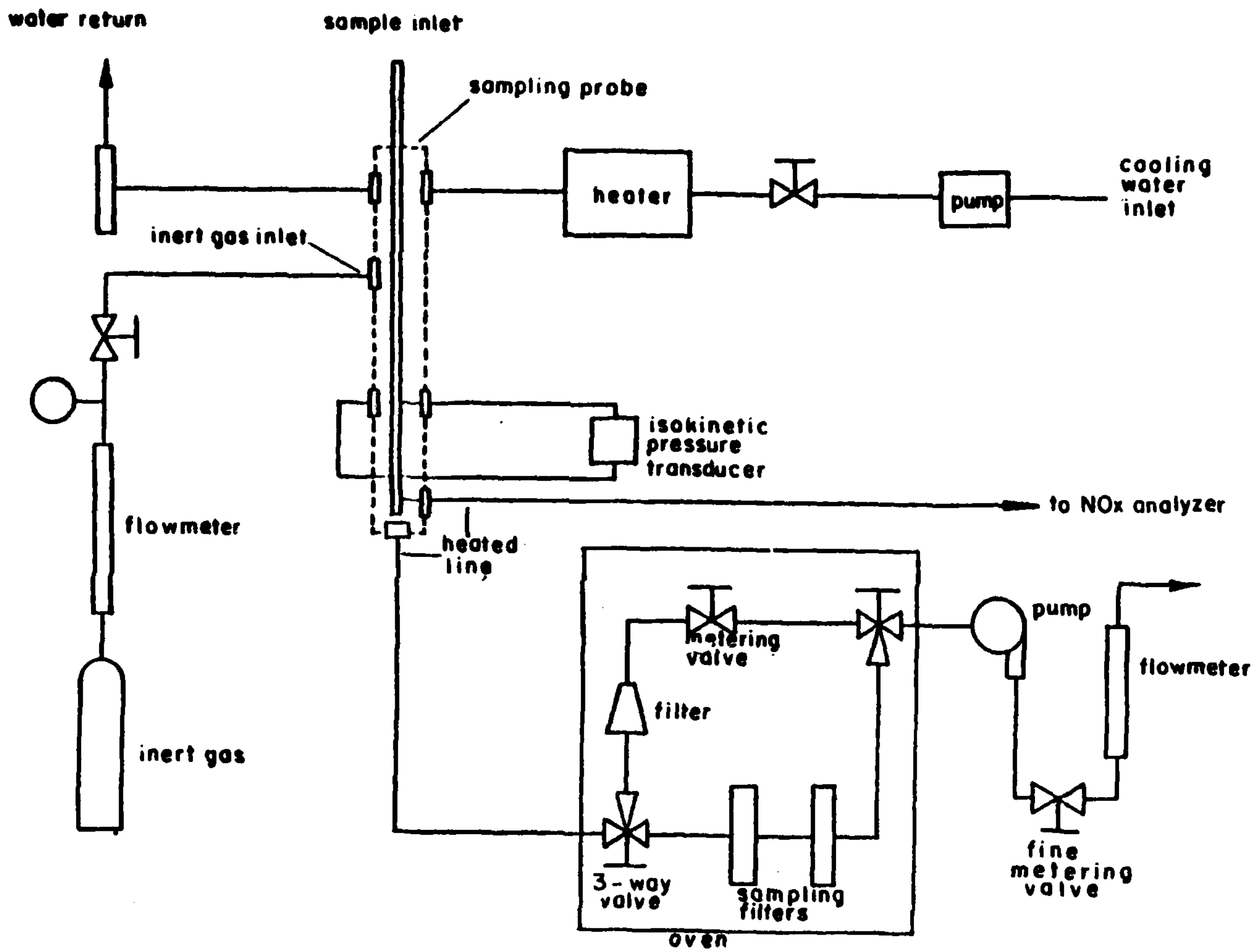


Figure 21. SCHEMATIC OF EXTRACTIVE PROBE SAMPLING SYSTEM

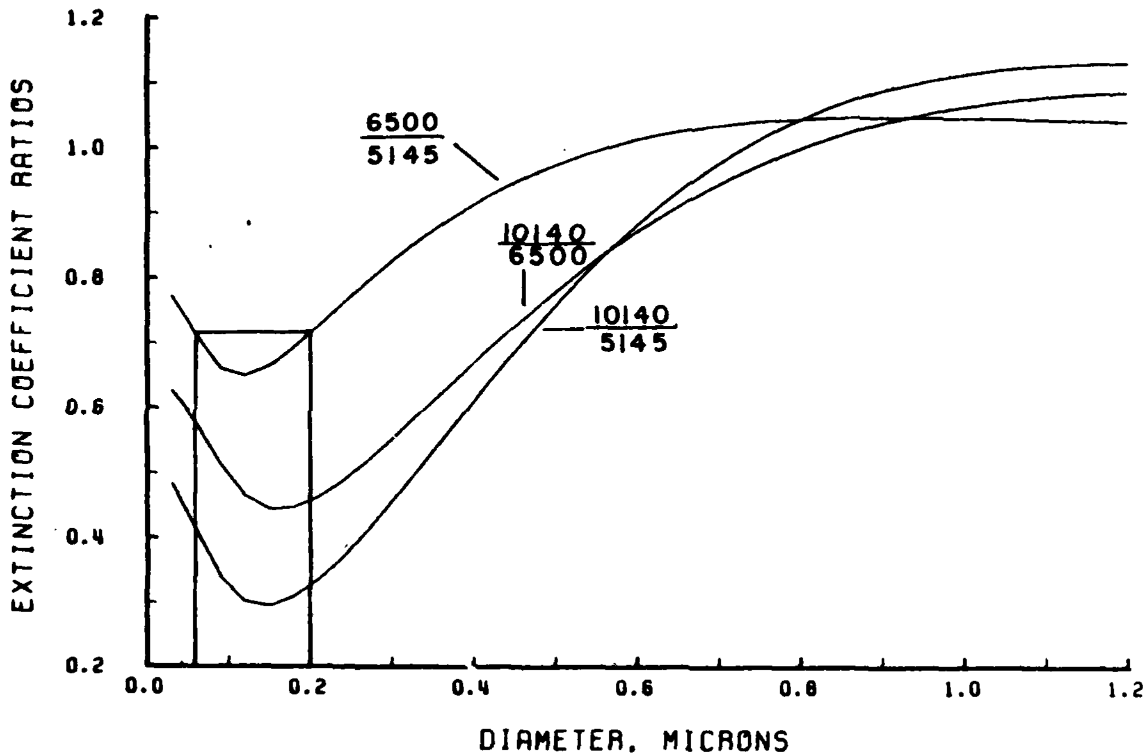
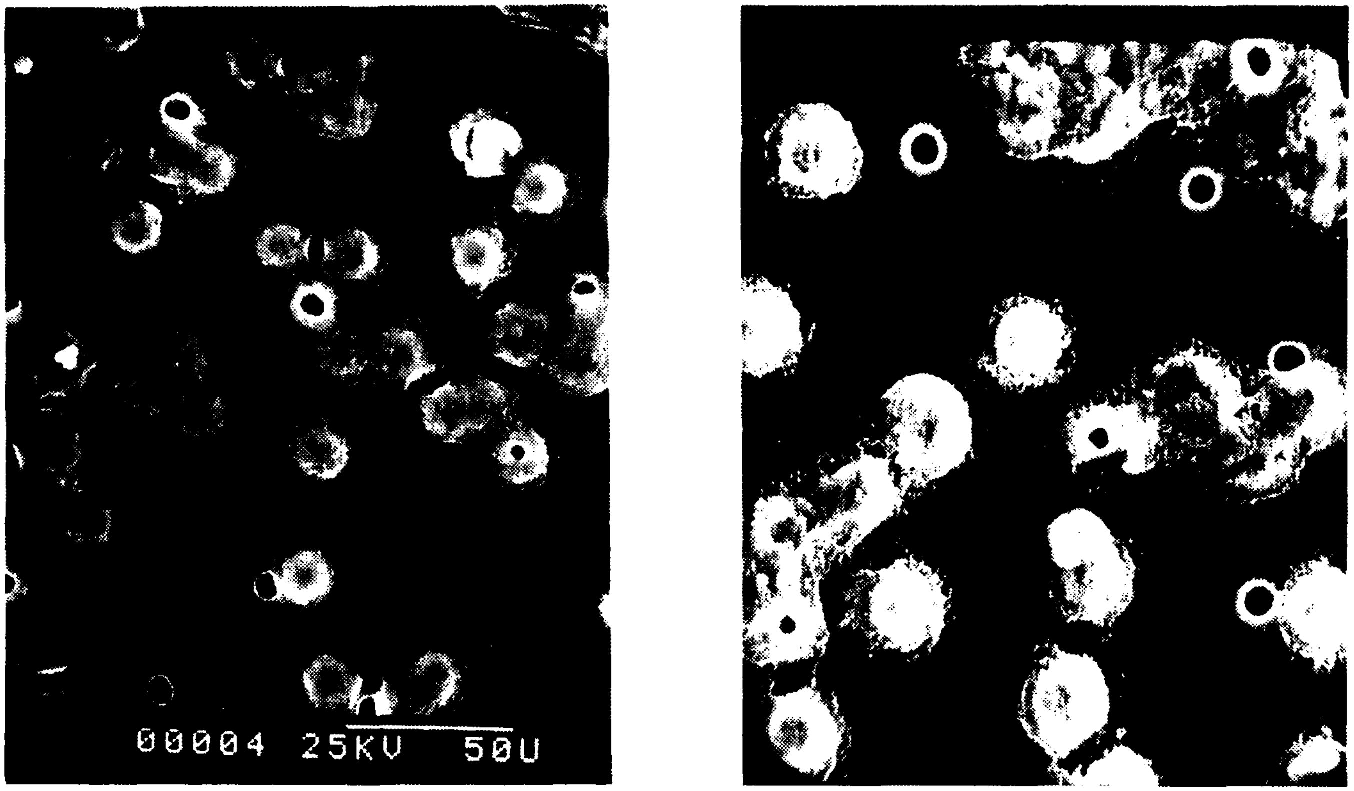


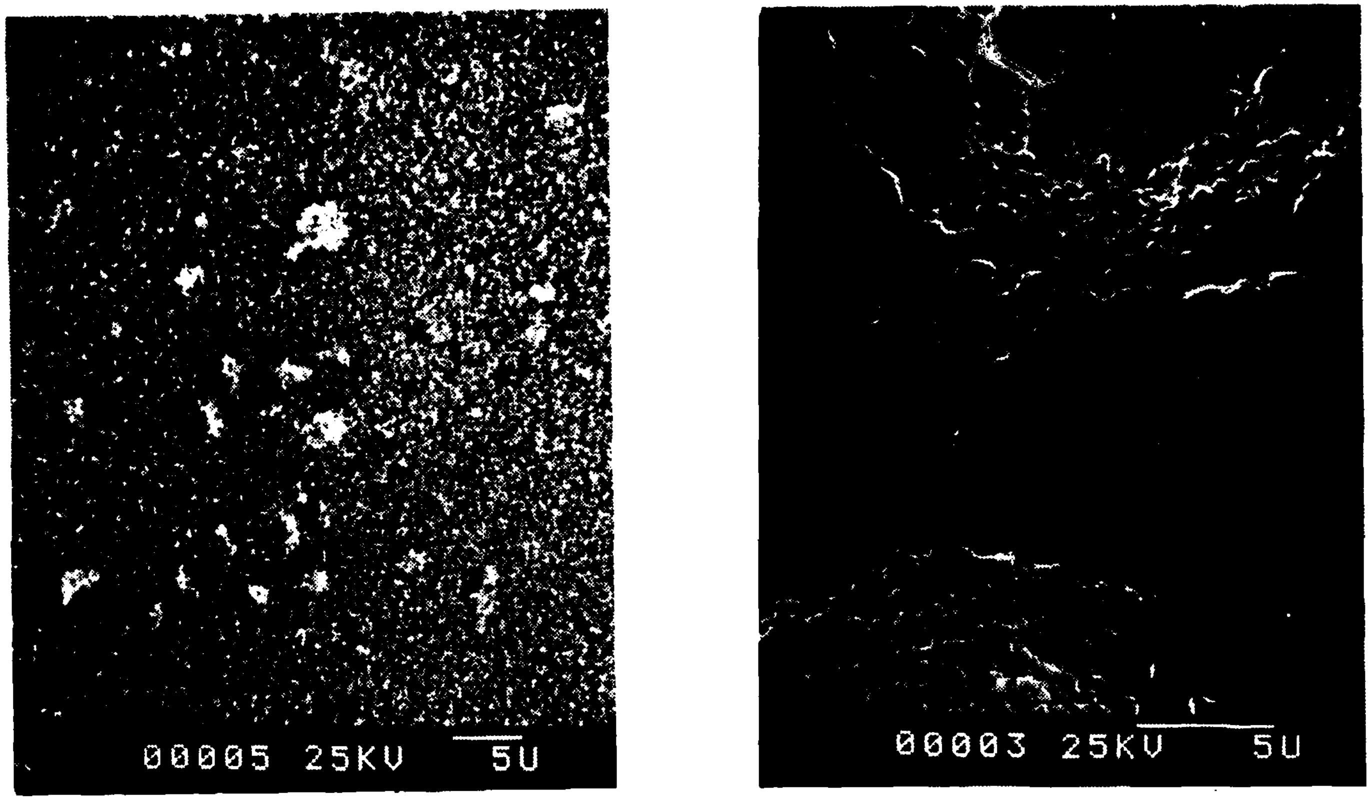
Figure 22. d_{32} VS. EXTINCTION COEFFICIENT RATIOS (10140, 6500, 5145); m=1.80-0.30i/1.5

Figure 23. SEM PHOTOGRAPH OF THE 8μm FILTER AT A MAGNIFICATION OF 200, GOLD PLATED



(a) (b)

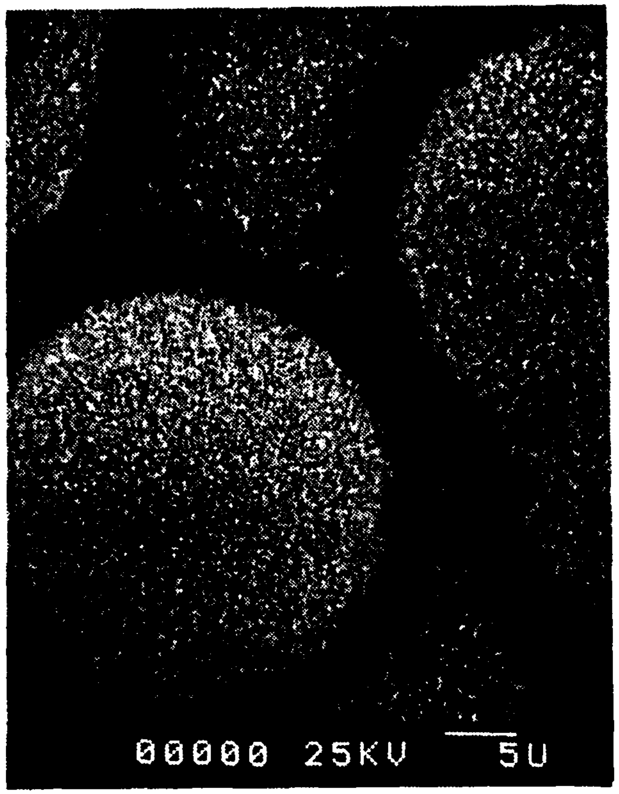
Figure 24. SEM PHOTOGRAPHS OF THE 8μm FILTER AT A MAGNIFICATION OF 500, ALUMINUM PLATED; (a) HITACHI S540 (b) CAMBRIDGE S4-10



(a) (b)

Figure 25. SEM PHOTOGRAPHS OF THE 8 μm FILTER USING THE HITACHI S540; (a) GOLD PLATED; MAGNIFICATION 2000 (b) ALUMINUM PLATED; MAGNIFICATION 4000

(a)



(b)

Figure 26. SEM PHOTOGRAPHS OF THE .2 μm FILTER (a) CAMBRIDGE S4-10; MAGNIFICATION 10,000, ALUMINUM PLATED; (b) HITACHI S540; MAGNIFICATION 2000, GOLD PLATED

(a)

(b)

Figure 27. SEM PHOTOGRAPHS OF THE .2 μm FILTER USING THE HITACHI S540; ALUMINUM PLATED; (a) MAGNIFICATION 10,000 (b) MAGNIFICATION 40,000

Table I.

TEST CELL FLOW RATES, TEMPERATURES, AND PRESSURES DURING TESTS

Run Number	$\dot{m}_a$ (lbs/s)	$\dot{m}_f$ (lbm/s)	f	T_{tP} (^oR)	T_E (^oR)	T_a (^oR)	P_C (psia)	P_a (psia)	ΔP_f (psi)	EQUIV-ALENCE RATIO (0)	$\overline{V}$ (m/s)
1	2.52	.04	.016	N/A	1572	5085	99	432	240	.23	22.4
2	N/A	N/A	N/A	N/A	1032	534	N/A	N/A	N/A	N/A	N/A
3	2.58	.039	.015	913	1580	492	100	435	240	.22	22.8
4	2.49	.039	.0155	887	1683	492	98	420	240	.23	23.9

Table II.

EXHAUST GAS OPACITY, TRANSMITTANCE VALUES, AND EXTINCTION COEFFICIENT RATIOS

		ENGINE			EXHAUST		
Run Number	Opacity (%)	T_λ 5145	T_λ 6500	$\bar{Q}_{6500}/\bar{Q}_{5145}$	T_λ 4500	T_λ 6500	T_λ 10140
1	7.3	.40	.57	.61	.98	.99	.96
2	6.04	.41	.64	.50	.93	.95	.94
3	7.0	.40	.68	.42	.98	.98	.99
4	7.0	.37	.70	.36	.99	.99	.98

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